THE EFFECTS OF VISUAL STABILITY INDEX (VSI) ON FRESH SEGREGATION OF SELF CONSOLIDATING CONCRETE (SCC) USING FLY ASH CLASS C AND F

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ABSTRACT

Self-consolidating concrete (SCC) is a concrete technology that is growing in popularity with the precast/prestressed industry and contractors. SCC increases the ease of concrete placement as well as reduces overall cost by requiring less labor and time for a concrete placement. This study is part of the proposed project by Tennessee Department of Transportation (TDOT) carried out by University of Tennessee at Chattanooga (UTC) to develop four new SCC mixtures (two Class P-SCC (precast) and two Class A-SCC (general use), and insure they meet the minimum strength and durability requirement for TDOT Class P and Class A mixtures. The objectives of the study presented in this thesis are to analyze a survey of state Departments of Transportation SCC specifications and requirements and investigate the effect of fly ash class and aggregate size and shape on fresh properties of Class A-SCC. In addition, investigate the relationship between Visual stability index (VSI) and fresh segregation of SCC. Finally, recommend the specifications of fresh performance requirements for the Class A-SCC that the Tennessee Department of Transportation (TDOT) should apply to establish SCC stability and flowability during the production of general concrete elements.

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CHAPTER 1

INTRODUCTION

1.1 Background

Self-consolidating concrete (SCC), also known as self-compacting concrete, is a highly flowable, non-segregating concrete; it has the ability of filling formwork under its own weight without the need of conventional vibration techniques. Generally, SCC is made with conventional concrete components with the addition of chemical admixture such as viscosity-modifying admixture (VMAs) to enhance cohesion and control the tendency of segregation resulting from the highly flowable SCC (ACI, 2007). Also, the amount of SCC fine aggregate is usually higher than that for conventional concrete in order to provide better lubrication for course aggregates to enhance workability of the mixture (Adekunle, 2012). The use of SCC was first used in Japan and has gained acceptance elsewhere since the late 1980s (ACI, 2007). During that time the durability of concrete structures became an important issue in Japan; thus an adequate compaction by skilled labors was required to obtain durable concrete structures. This requirement led to the development of SCC and its first use was reported in 1989 (Okamura & Ouchi, 2003). SCC was initially used to provide proper consolidation in applications where concrete durability and service life were of concern. Later, SCC was also proven to be economically beneficial because of a number of factors as noted below (EFNARC, 2002):

- Accelerating construction times.
- Reduction in site manpower and equipment.

- Improved finished surfaces
- Improved ease of placement
- Improved durability
- Greater freedom in design
- Thinner concrete sections
- Reduced noise levels, absence of vibration
- Safer working environment

The use of SCC has been an excellent solution for the precast/prestressed concrete industry. In the precast industry, congested reinforcement and complex geometrical shapes make proper filling and consolidation using conventional concrete more difficult. In addition, due to the relative ease of construction using SCC and superior quality control environment that is required in the precast industry SCC use has been a relatively easy transition. In North America, the use of SCC in the precast industry has grown dramatically since 2000. In 2000 the volume of SCC in the precast market was approximately 177,000 yd^3 (135,000 m^3) and it increased to 2.3 million yd^3 (1.8 million m^3) in 2003 (ACI, 2007). In 2002, 40% of precast manufactures in the United States had used SCC, and in some cases, new plants are currently being built around the idea of using SCC technology (Vachon & Daczko, 2002).

Besides the above advantages, SCC has also been proven to have some disadvantages related to its fluid nature. SCC is a highly flowable concrete; therefore formwork must be properly sealed and strong enough to inhibit leaking of the SCC paste and resist the higher hydrostatic pressures that are expected with fluid SCC (Keske, Schindler, & Barnes, 2013). Also, more studies are needed to study the effects of adding chemical admixtures that give SCC its fluid nature, higher paste contents, and higher fine contents that may significantly change the fresh and hardened properties of the SCC compared to conventional concrete mixes (Missouri DOT, 2012).

1.2 Objectives and Scope of work

Self-consolidating concrete (SCC) is a concrete technology that is growing in popularity with the precast/prestressed industry and contractors. SCC achieves the ability to flow and self-consolidate through modified aggregate gradations, increased cementing materials, and chemical admixtures; therefore, its hardened properties are similar to conventional concretes. This study is part of a project funded by Tennessee Department of Transportation (TDOT) carried out by University of Tennessee at Chattanooga (UTC) to develop four new SCC mixtures; two Class P-SCC (precast) and two Class A-SCC (general use), and ensure they meet the minimum strength and durability requirement for TDOT Class P and Class A mixtures. The research program will insure that desired fresh properties are achievable with materials available in Tennessee. With the approval of TDOT management, Class P-SCC and Class A-SCC (with specified fresh and hardened properties) would appear as an option in TDOT specifications. Using SCC mixtures can potentially save TDOT money by allowing TDOT suppliers and contractors to utilize this cost and time saving technology. In addition, greater use of supplementary cementing materials (SCMs) will improve TDOT's environmental stewardship.

As stated, this study is part of the TDOT research to investigate the fresh and hardened properties of SCC. Throughout this study, only the class A (general use) mixtures were selected for detailed studies of their fresh properties. Therefore the development of the class P (precast) mixtures is out of the scope of this study. The primary objectives of this study were thus to:

- Investigate the fresh properties of Class A-SCC in comparison to conventional concrete.
- Investigate the relationship between Visual Stability Index (VSI) and fresh-segregation of Class A- SCC
- Investigate the effect on fresh properties of fly ash Classes C and F, and various gradations of coarse and fine aggregates.
- Recommend the specification of fresh performance requirements for the general use (Class A) SCC that the Tennessee Department of Transportation (TDOT) should apply to establish SCC stability and flowability during the production of general elements.

To achieve the above objectives the following scope of work was implemented: (1) review other States' specifications and relevant studies and literature; (2) develop a research approach; (3) investigate the fresh properties of general use SCC mixes; (4) investigate the effects of VSI on fresh segregation of SCC mixes; (5) compare the fresh properties of SCC mixes with conventional concrete mixes; (6) analyze and study the information obtained throughout the mixing and testing to develop findings, conclusions, and recommendations; and (7) prepare this study in order to document the information obtained during this investigation, and provide the TDOT with the specification of fresh performance requirements for SCC for the general use (Class A) .

1.3 Research Approach

The study was executed in six activities. The first activity involved conducting a comprehensive literature review and survey the state Department of Transportation (DOT) SCC specifications. The State DOT SCC survey and specifications were reviewed and summarized in Chapter 3. These specifications were used as a guide to develop the candidate mixture proportions and the specification of their fresh and hardened properties.

In the second activity, typical Class A materials such as Supplementary Cementitious Materials (SCMs), coarse aggregate, fine aggregates, cement, Classes C and F fly ash, and some chemical admixtures were acquired from local TDOT suppliers. Also, in this activity, the test specimens molds and experimental accessories were prepared as well as necessary equipment calibration was conducted.

The third activity involved the development of candidate Class A-SCC mixtures. Two Class A-SCC mixtures were developed, with 20% replacements of cement with Class F fly ash and Class C fly ash. These mixture proportions were developed based on the trial minimum requirement determined in activity one. Several conventional concrete mixtures were developed for the Class A to evaluate the performance of the SCC mixes in comparison to conventional concrete. A total of 12 batches of each candidate mixture were developed using different coarse aggregate gradations, natural and manufactured sand as described in Section 4.

In the fourth activity, the 12 batches of each candidate mixture (24 totals) were tested with a variety of fresh consistencies and aggregate blends. Each Conventional mixture underwent standard fresh property testing which includes: slump (ASTM C 143); Unit Weight and Gravimetric Air Content (ASTM C 138); Air Content by Pressure Method (ASTM C 231). In addition SCC mixtures underwent the same fresh test except slump, and underwent additional fresh tests which include: Slump Flow and Visual Stability Index (ASTM C 1611); Consolidating ability by J-Ring (ASTM C 1621); Static Segregation by Column Test (ASTM C 1610); and L-Box.

Castings of SCC specimens for the proposed hardened tests on the candidate mixtures, which are outside the scope of this study, will be carried out in the fifth activity. Each Class A-SCC mixture will be tested at 7, 28, and 56 days. Each mixture will undergo standard hardened property testing which includes: compressive strength, splitting tensile strength, modulus of elasticity, rapid chloride permeability, and hardened concrete segregation by ultrasonic pulse velocity.

In the final activity, the fresh properties data were compiled, analyzed and the effects of Visual Stability Index (VSI) on fresh segregation of SCC was investigated. The final task of this project, which is not in the scope of this thesis, will be to prepare the final report including the entire study and conclusions will be compiled from the experimental results and recommendations will be provided.

1.4 Study Outline

This study consists of six chapters. Chapter 1 discusses the history, advantages, and disadvantages of using SCC. Also within Chapter 1, the objectives, scope of work, and research approach are discussed.

The existing literature relating to all aspects of this study is summarized in Chapter 2. The mixture proportioning as well as the fresh properties of SCC is discussed. Also, Stability and fresh segregation of SCC, followed by a summary of the methods used to assess the fresh properties are addressed.

Chapter 3 summarizes the survey of state Departments of Transportation (DOTs) that was conducted to gather specifications related to SCC use in other states. The survey addresses the mixture parameters, fresh performance, and hardened performance requirements. The results of the survey were summarized and discussed in chapter 3.

Section 4 documents the development of the 16 SCC mixtures and 8 conventional concrete mixtures. A detailed description of theses mixtures is discussed which includes, but are not limited to, the selection of aggregate gradation, cementation materials, chemical admixtures, and air entrained admixture. Also, the mixing procedure is documented, followed by descriptions of the fresh properties measured during this study.

The results of the fresh SCC tests are presented in Chapter 5. All conclusions and recommendations derived from the study are then summarized in Chapter 6.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Self-consolidating concrete (SCC) is a new technology in the market and it is rapidly growing particular in the precast industry because of its economic benefits and due to the relative ease of construction and superior quality control environment in that industry segments. SCC has been described as "the most revolutionary development in concrete construction for several decades (Vachon & Daczko, 2002). As mentioned earlier, SCC is highly flowable and it is made with conventional concrete components with chemical admixture such as viscosity-modifying admixture (VMAs) to enhance cohesion and control the tendency of segregation resulting from the highly flowable SCC. Generally, SCC achieves the ability to flow and self-consolidate through modified aggregate gradations, increased cementing materials, and chemical admixtures; therefore, its hardened properties are similar to conventional concretes but its fresh properties differentiate it from conventional concrete. SCC should be designed to provide high levels of deformations while maintaining highly stability. Therefore, the fresh properties of SCC are vital in determining whether or not it can be placed satisfactorily and with the required characteristics. The main four characteristics that should be met for SCC are mentioned below (ACI, 2007):

- Filling ability (unconfined flowability): The ability of the SCC to flow and fill completely all spaces within a mold or form under only self-weight.

- Passing ability (confined flowability): The ability to flow through reinforcing bars or other obstacles without segregation and without mechanical vibration.
- Segregation resistance (stability): The ability to remain homogeneous in composition during transport and placing.
- Surface quality and finishing.

Throughout this chapter, the most commonly used test methods that are conducted to measure the SCC characteristics are briefly described. Also a brief description of material proportion and hardened properties of SCC are discussed.

2.2 Test Methods for Measuring SCC Characteristics

Most of the conventional fresh property tests are not applicable to SCC due to its high flowable nature. Thus, there are many methods that were derived in order to test the fresh properties and characteristics of SCC, which are briefly described below:

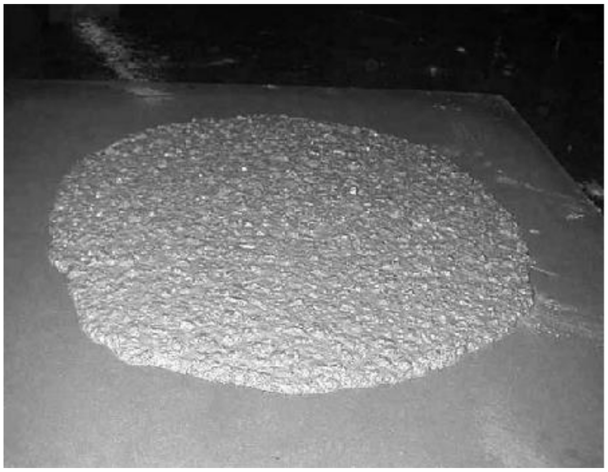
2.2.1 Slump Flow Test (ASTM C 1611)

The slump flow is the most widely used test to measure the filling ability and flowability of SCC (ASTM, 2005). It was first developed in Japan to characterize fresh concrete mixtures for under-water placement (ACI, 2007). The test method is based on the conventional slump test. The diameter of a SCC "patty" is measured. This patty is formed from SCC free flowing from an inverted slump cone onto a level surface. The common range of slump flow that is reported by ACI Committee 237 is 18 to 30 inches (450 to 760 mm) for SCC. The higher the slump flow value, the greater ability to fill formwork or mold, and the farther the SCC can travel from a discharge point under self-weight. An example of a slump flow test is shown in Figure 2.1.

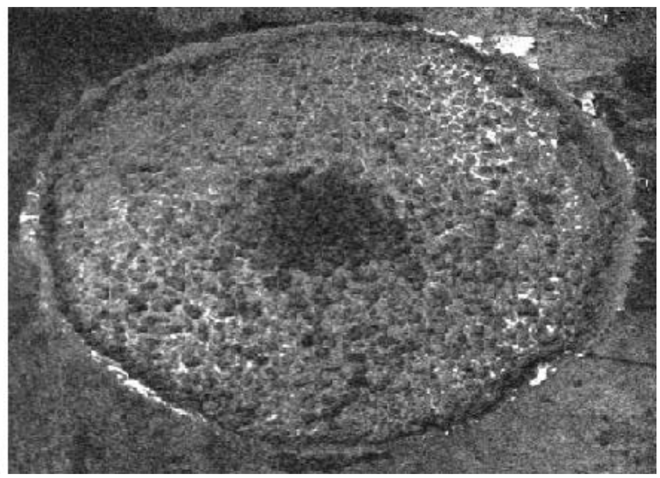
Figure 2.1 Slump flow test

2.2.2 Visual Stability Index (ASTM C 1611)

The Visual Stability Index (VSI) is a method for determining the segregation stability of the mixture, and to evaluate the relative stability of batches of the same SCC mixture. The VSI is determined through visually rating apparent stability of the slump flow patty based on specific visual properties of the spread. The SCC mixture is considered stable and suitable for the intended use when the VSI rating is 0 or 1, and a VSI rating of 2 or 3 gives an indication of segregation potential (ACI, 2007). Assigning a Visual Stability Index (VSI) value to the concrete spread using the criteria shown Figure 2.2 (ASTM, 2005).



(a) (b)



(c) (d)

Figure 2.2 Visual Stability Index, (a) VSI = 0 – Concrete Mass is Homogeneous and No Evidence of Bleeding. (b) VSI = 1 – Concrete Shows Slight Bleeding Observed as a Sheen on the Surface. (c) VSI = 2 – Evidence of a Mortar Halo and Water Sheen. (d) VSI = 3 – Concentration of Coarse Aggregate at Center of Concrete Mass and Presence of a Mortar Halo.

2.2.3 T50 (ASTM C 1611)

The T50 value is another fresh property to quantify the flowing ability of SCC, and provides a relative index of the viscosity. The test measures the time for the slump flow paddy to reach a diameter of 20 in (50 cm). A longer T50 time indicates a higher viscosity mixture, and a shorter T50 results from a lower viscosity mixture (ACI, 2007). ACI Committee 237 reports that a SCC mixture can be characterized as a lower viscosity mixture when the T50 time is 2 seconds or less, and as a higher viscosity mixture with T50 time greater than 5 seconds. The T50 test and slump flow test are typically performed with the same paddy.

2.2.4 J-ring (ASTM C 1621)

The test is used to determine the passing ability of SCC through reinforcement steel and obstacles. A sample of fresh SCC is placed in a standard slump cone with J-ring based, which contains steel bars. The mold is raised, the SCC passes through J-ring, and the J-ring patty diameter is measured (ASTM, 2009a). The higher the J-ring slump flow value, the greater ability the SCC has to fill a steel reinforced form or mold, and the farther SCC can travel through a reinforcing bar from a discharge point under its own weight (ACI, 2007). The difference between the unconfined slump flow and the J-ring slump flow is used to identify the restriction degree of SCC to pass through reinforcing bars. The mixtures passing ability and the blocking tendency could be identified according to the ASTM C1621 standard classification shown in Table 2.1. An example of a J-Ring test is shown in Figure 2.3.

Table 2.1 Blocking assessment using J-ring

Difference Between Slump Flow and J-Ring Flow	**Blocking Assessment**
0 to 1 in.	No visible blocking
>1 to 2 in.	Minimal to noticeable blocking
>2 in	Noticeable to extreme blocking

Figure 2.3 J-Ring test

2.2.5 L-box Test

The L-box test is based on a Japanese design for underwater concrete (EFNARC, 2002). The test assesses the flow of the concrete, and also the extent to which it's subject to blocking by reinforcement. The apparatus consists of a rectangular-section box in the shape of an 'L', with a vertical and horizontal section, separated by a moveable gate, in front of which vertical lengths of reinforcement bar are fitted. The SCC is placed in the vertical section, and the gate is lifted to let the concrete flow into the horizontal section. When the flow stops, the heights of the concrete are measured at the end of the horizontal section and in the vertical section. The L-Box result is the ratio of the height of concrete in the horizontal section to remaining in the vertical section. ACI Committee 237 specified the minimum ratio of the heights to be 0.8, and the nearer this ratio to 1.0 is the better flow potential of the SCC mixture. An example of L-Box testing apparatus is show in Figure 2.4.

Figure 2.4 L-Box testing apparatus

2.2.6 Column Segregation (ASTM C 1610)

This test is used to assess the segregation resistance of SCC. A sample of freshly SCC is placed in one lift in a cylindrical mold without tamping or vibration. The mold is rested for 15 minutes, and then the cylindrical mold is divided into three sections to represent different levels of the column. The SCC from the top and bottom sections is washed through a No.4 (4.75 mm) sieve, leaving the coarse aggregate on it. The mass of the coarse aggregate from the top and the bottom levels of the column are determined in order to calculate the percentage of segregation (ASTM, 2009b). The SCC is generally considered to be accepted if the percent segregation is less than 10% (ACI, 2007). An example of a column segregation test apparatus is shown in Figure 2.5.

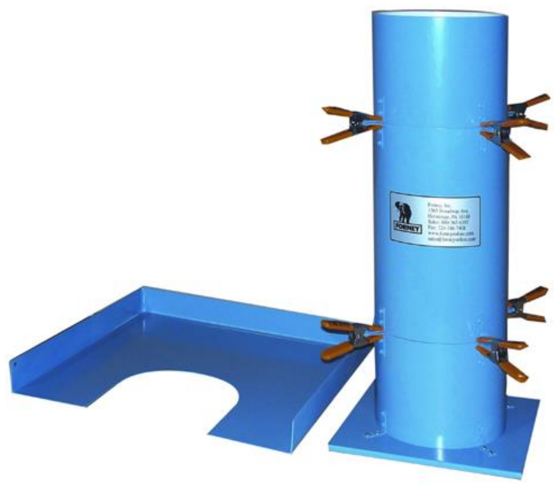


Figure 2.5 Column segregation apparatus

2.3 Constituent Materials and Mixture Proportions of SCC Mixtures

SCC is made with conventional concrete components which includes, coarse and fine aggregate, cement, supplementary cementing materials, water, air, and with some chemical admixture such as high-range water reducers and VMAs (ACI, 2007). In addition, SCC contains larger amount of powder and supplementary cementitious materials such as fly ash, silica fume, GGBFS, limestone powder, etc. in order to enhance the behavior of SCC.

2.3.1 Powders and Water Content

Powder includes cement, GGBFS, fly ash, Limestone powder, and any material that grinds to less than 0.125 mm (No.100 sieve) (ACI, 2007). SCC is comprised of a large amount of powders that can improve the characteristics of SCC, particles distribution and packing, and ensuring high cohesive SCC.

2.3.1.1 Portland Cement

The selection of the type of cement based on the overall requirements of SCC such as strength, durability, and the application (Keske et al., 2013; PCI, 2003). For general use concrete, the cement should not contain more than 10% of C_3A to avoid the problems of poor workability and quick hydration (Hameed, 2005). Therefore most types of the five primary types of Portland cement can be used in SCC and they should meet one of the flowing specification: ASTM C 150, C 595, or C 1157 (ACI, 2007). For precast/prestressed concrete, ASTM C 150 type III cement is preferred due to its high early-age strength characteristics (K. H. Khayat, 1999).

2.3.1.2 Fly Ash

Fly ash is spherical with smooth surface particles, resulting from the burning of coal in coal fired power plants. ASTM C 618 separates fly ash into two classes based on the calcium oxide content, Class C which contains 15 – 40 percent of calcium oxide, and Class F, which has less than 10 percent calcium oxide (ASTM C 618, 2003). Fly ash is used to replace portland cement to decrease the cost and heat of hydration associated with Type III cement. According to ACI 2007 and Khayat et al. (2003) a replacement between 20 and 40% Class F fly ash in a SCC mixture led to good workability, with acceptable strength development and frost durability.

However some studies showed using Class F fly ash can reduce the early strength at three and seven days (Keske et al., 2013; Mehta & Monteiro, 2006). Optimum replacement value is determined by job specification, material availability, cost, and the strength-gain needs of the application (ACI, 2007; Keske et al., 2013).

2.3.1.3 Mixing Water

The relationship between water-to-cementitious-material ratio (w/cm) and the strength of concrete is an inverse relationship; the strength increases if the w/cm decreases (Keske et al., 2013; Mehta & Monteiro, 2006). For precast concrete highly early-age strengths are desirable, thus a lower w/cm should be applied, typically between 0.34 and 0.40 (Keske et al., 2013; Kamal Khayat & Mitchell, 2009). Therefore, high range water reducers admixtures (HRWRA) are used to increase the workability of SCC mixtures. Also, the stability of SCC could be increased by reducing the water content; thus, a suitable amount of water and water reducer is needed to maintain higher level workability and stability.

2.3.2 Coarse Aggregate and Fine Aggregate

The coarse aggregate size and volume should be chosen according to the required SCC characteristics (passing ability and stability of the plastic concrete) (ACI, 2007). The passing ability of SCC is very sensitive to the size and volume of coarse aggregate. Therefore, ACI committee 237 recommends the nominal maximum size of the coarse aggregate to be one size smaller than recommended in (ACI Committee 301, 1994) to enhance the passing ability. The particle shape of coarse aggregate also affects the workability of SCC. A rounded coarse aggregate provides more filling ability than a crushed-stone of similar size (ACI, 2007) . The fine aggregate, on the other hand, should be well-graded natural or manufactured sand. In general, it is recommended to blend natural and manufactured sand to improve the stability of SCC (ACI, 2007).

Generally, the decrease in total coarse aggregate volume enhances the passing and filling ability of SCC mixtures (Keske et al., 2013; Koehler et al., 2007). In precast/prestressed application, where a high passing and filling ability are required, the coarse and fine aggregate could occupy one third of SCC mixture by volume each (Keske et al., 2013; Kamal Khayat & Mitchell, 2009; Koehler et al., 2007).

2.3.3 Admixtures

Admixtures are an effective component in SCC mixtures. There are many types of admixtures that are used to enhance the fresh properties of SCC mixtures such as, but are not limited to, high-range water-reducer admixtures (HRWRAs), Viscosity-Modifying Admixtures (VMAs), and Air –Entraining admixtures (AEA).

HRWRAs are the most common admixtures that can be used to develop SCC mixtures. Generally, HRWRAs increase the fluidity of SCC which helps to maintain the water cement ratio as lower as possible (ACI, 2007). HRWRAs can affect the fresh properties of SCC through increasing the workability, and the hardened properties, especially strength, are affected by reducing the w/cm as a result of using HRWRAs (Keske et al., 2013).

Viscosity-Modifying Admixtures are beneficial components for controlling the viscosity and stability of SCC. A lower viscosity, lower resistance to flow, is required to increase the traveling distance of SCC during the placement (Keske et al., 2013; Koehler et al., 2007). VMAs can also be used with HRWRs to maintain a uniform stability at a lower viscosity (Keske et al., 2013; K. H. Khayat, 1999). In general, the use of VMAs is not always necessary, the viscosity of SCC mixture can be adjusted through aggregate selection and graduation, or by controlling the amount of water reducer admixtures and viscosity-modifying admixtures (Keske et al., 2013; KH Khayat, Ghezal, & Hadriche, 2000; Koehler et al., 2007).

Air-Entraining Admixtures are added to concrete to form macroscopic voids and microscopic bubbles in the concrete volume to provide space for concrete expansion due to the cyclic freezing and thawing of water caught inside the concrete. AEA provides a uniform structure of voids, thus making their use popular in precast SCC mixtures (Keske et al., 2013). Generally, AEA is applied in small dosages; the dosage must be adjusted based on the concrete fluidity and production techniques employed (Keske et al., 2013).

CHAPTER 3

SURVEY OF THE STATE SCC MATERIAL SPECIFICATIONS

3.1 Introduction

A survey of state Departments of Transportation (DOTs) was conducted to gather specifications related to SCC use in other states. The survey addresses the mixture parameters, fresh performance requirements, and the hardened performance requirements. The results of the survey are summarized and discussed in this chapter. In the summary the term "general" will be used to describe specifications that allow for multiple uses or where a particular use is not explicitly stated.

3.2 Survey Requirements

The survey was distributed to the state DOTs in the US to gather information related to SCC specifications. The survey addresses the mixture parameters, fresh performance, and hardened performance requirements; the items specifically addressed by the survey are:

3.2.1 Mixture Parameters

- Maximum and minimum cement contents.
- Fly ash (and other SCM) usage allowances.
- Coarse aggregate gradation (maximum size) limits.
- Fine-to-total aggregate ratio limits (FA/TA).

- Air entrainment requirements (AE).
- Water-to-cement ratio requirements.

3.2.2 Fresh Performance

- Slump flow maximum/minimum limits.
- T-50 limit.
- Visual stability (VSI) limit.
- J-Ring, L-Box, segregation column, and/or other fresh performance requirements.

3.2.3 Hardened Performance

- Compressive strength requirements.
- Flexural/tensile strength requirements.
- Modulus of elasticity requirements.
- Permeability requirements.

3.3 Summary of The Survey

A summary of the 24 state DOTs that responded to the survey is shown in Figure 3.1. Oregon and Michigan responded that they do not allow SCC on their projects, and South Carolina responded that there was no industry demand for SCC. Of the states that use SCC, the survey results showed that 12 states allow for SCC in precast application through specification or special provision. Seven states allow SCC for general use through specification or special provision. SCC in drilled shaft foundations is allowed in 4 states through special provision or specification. Three states allow SCC for other uses (caissons, bridges, and composite arch).

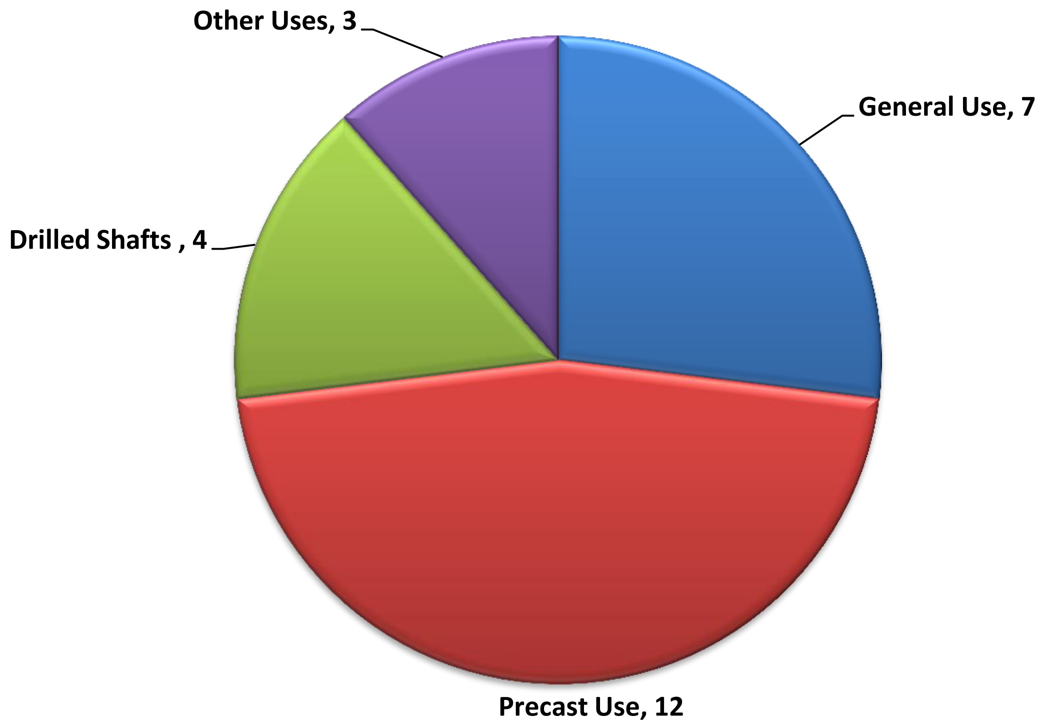


Figure 3.1 Summary of SCC usage type among responding states

3.3.1 Summary of the Respondents

Survey was sent to 50 states and responses to the survey were received from 24 states. The specifications of the states that responded are briefly summarized in the next section and details are provided in Tables 3.1 - 3.5. The respondents generally indicated they do have some specifications for mixture parameters and fresh performance requirements; however hardened properties, especially flexural strength, tensile strengths, and permeability were reported to be project-specific.

3.3.1.1 Alabama (ALDOT)

The SCC specifications for ALDOT are in the process of being finalized. However, they provided parameters which are applicable for SCC use in prestressed concrete. The parameters include the mixture proportions, fresh performance requirements, and the hardened performance requirements for SCC for precast use. They have specified 5000 psi compressive strength unless otherwise specified. For their permeability requirement they have specified a maximum 2,000 coulombs in marine environments. Currently ALDOT is considering the use of SCC for use in drilled shafts and columns.

3.3.1.2 Arizona (ADOT)

ADOT responded with the requirements they are using to approve SCC for precast. The parameters include the mixture proportions, in which they base the cement content loosely off of the requirements for structural concrete. The SCM content is up to the manufacture, but ultimately has to be review and approved by the department. They do not require air entrained in precast or prestressed items. They do not have a FA/TA limit, but they stated they have not approved a mixture with a FA/TA of more than 0.48. There are no requirements for maximum aggregate size, but they report a #7 stone is typical. Column segregation is required during trial batching, and typically monthly during production. Compressive strength is the only hardened performance requirement and it is as per specification.

3.3.1.3 California (Caltrans)

Caltrans provided general specifications for SCC, and it applies only where the job specifications allow the use of SCC. The provided specification allows for SCC use in several applications and is labeled general purpose for this report. The specifications contain the fresh performance requirements, the coarse aggregate gradation limits, and the SCMs usage allowance which include: fly ash, GGBFS, ultra-fine fly ash (UFFA), and metakaolin.

3.3.1.4 Colorado (CODOT)

Colorado State provided information on their specifications for SCC for use in caissons and precast. However, there were no specifications for precast use.

3.3.1.5 Florida (FLDOT)

FLDOT provided their specifications for the precast/prestressed concrete fabrication facilities that are involved in the manufacturing of the products using SCC. The specifications contain the mixture parameters requirements in which they do not mandate a coarse aggregate maximum size. Producers are using #67, #78 or #89 and may include additional blending of these; however, to avoid shrinkage concerns produces are trying to use #67 and #78 maximum sizes. The cementing and SCM requirements are the same as that for conventional concrete. The air entrainment requirement is 1% to 6%. The specifications also provide the fresh and hardened performance requirements which are a project-specific.

3.3.1.6 Idaho (ID DOT)

Idaho State SCC specifications are a modification of the Portland cement concrete specifications. The SCC specification provided is for Class 30 (3000psi) and Class 35 and greater (3500psi and greater) concrete. It contains the mixture parameter requirements, and the fresh performance requirements.

3.3.1.7 Kentucky (KY DOT)

Kentucky DOT reported that SCC is only permitted for qualified precast plants. The SCC strength requirement is 3500psi for 28 days unless otherwise indicated in project plans. They specified the cement content, air entrainment, and the water-to-cement ratio requirements in the mixture parameters section.

3.3.1.8 Maine (ME DOT)

Maine DOT reported in their draft specifications that SCC can be used for Class A (general use), LP (Structural Wearing Surfaces) or P (Precast) mixes when approved by the Resident Engineer. The SCC should meet the requirements of strength, entrained air and permeability for the respective concrete Class.

ME DOT also provided a special provision for SCC that they used on bridge project using carbon-fiber composite arches. The special provision contains the mixture parameters, fresh performance requirements, and the compressive strength.

3.3.1.9 Maryland (MD SHA)

Maryland Department of Transportation's State Highway Administration (SHA) has been conducting a pilot program using SCC in a selected number of precast plants producing low-risk drainage structures for a number of years. Recently the Maryland Transportation Authority (Maryland's tolling authority) completed a large-scale project, the Inter-County Connector, which incorporated a number of prestressed beams utilizing SCC. SHA provided their current draft specification for SCC in precast and prestressed structures which contains the mixture parameters, fresh performance requirements, and the hardened performance requirements.

MD SHA administers some 30+ precast/prestressed plants over a ten state region. Due to the degree of variance in aggregate properties and variable needs for ASR mitigation, MD SHA does not set absolute aggregate limits. Trial batch results will indicate need for adjustment to aggregates and SCM. MD SHA reports none of their producers are currently manufacturing a SCC mixture with any stone or gravel larger than #67.

3.3.1.10 Michigan (MI DOT)

MIDOT reported they do not allow SCC usage in their projects.

3.3.1.11 Minnesota (MN DOT)

Minnesota State DOT provided their draft performance specifications for SCC. They do not have a standard specification for SCC at the present. They have used SCC on a couple of projects, when there were concerns about achieving consolidation around heavily reinforced locations. In those cases, they use conventional concrete specifications and added requirements for a VSI of less than 1 and a maximum spread of 28".

3.3.1.12 Mississippi (MS DOT)

Mississippi DOT provided information regarding SCC specifications for general use and drilled shafts concrete. The specifications are comprised of the mixture parameter requirements which include SCM usage, maximum size aggregate, air content and w/c. For fresh properties they specify slump flow separately for precast and general use. In addition, they specify J-ring, static segregate (column test) and bleeding capacity.

3.3.1.13 New Hampshire (NH DOT)

New Hampshire DOT has used SCC in precast operations, and they have an Alkali–silica reaction (ASR) and permeability requirement in which suppliers must use SCMs. For the fresh performance requirements they responded that all the mixtures used for NHDOT have been developed by precast manufacturers with assistance of admixture suppliers. A fields test is required prior to placement to insure the adequacy of the mixture. However, they do not report specific requirements for the fresh performance properties. NHDOT reported they have minimum compressive strength and permeability requirement for the hardened performance requirements, but they did not specify their values.

3.3.1.14 New Jersey (NJDOT)

New Jersey provided their SCC specifications for drilled shafts and precast concrete. The specifications contain the mixture parameters and the fresh performance requirements, and they specified the compressive strength and the permeability in the hardened performance requirements.

3.3.1.15 North Carolina (NCDOT)

NCDOT provided the standard special provision for SCC for Precast / Prestressed use. It contains the mixture parameters, fresh performance requirements, and specifies the compressive strength for hardened performance requirements.

3.3.1.16 Nevada (NV DOT)

Nevada Department of Transportation allows SCC only in drilled shafts. A minimum of 20% fly ash is required. There is no requirement for maximum aggregate size but 1/2 inch is typical. There is no specification for FA/TA but the mixtures range from0.57-0.43.

3.3.1.17 Oregon (OR DOT)

Oregon DOT reported they do not allow SCC usage in their projects.

3.3.1.18 Rhode Island (RIDOT)

RIDOT provided the general specification for SCC which covers the requirements for modifying all classes of concrete mix designs, except classes B (General Use) and Z (Precast Elements) for self-consolidating applications. RIDOT does not have different requirements for conventional and SCC mixtures except for the maximum water/cement ratio, slump and placement methods.

3.3.1.19 South Carolina (SCDOT)

SCDOT does not have specifications for SCC in their standard specifications. They stated that the prestressed concrete producers in their state are not interested to work with the SCC mixture, and that they would rather work with a high slump conventional concrete. However, a few years ago, University of South Carolina (USC) conducted a research study of SCC funded by SCDOT to investigate the performance and the benefits of lightweight SCC prestressed concrete bridge girders.

3.3.1.20 South Dakota (SDDOT)

South Dakota DOT provided their current special provision for cast-in-place SCC which is a modification of the SDDOT Standard Specifications for Roads and Bridges for conventional concrete. The specification addresses the mixture parameters and the performance requirements for general use.

3.3.1.21 Texas (TXDOT)

TxDOT provided their 2014 concrete specifications. They have allowed SCC concrete in precast concrete plants that produce girders, retaining walls, and coping for several years. Currently they don't allow SCC concrete on the jobsites, but they might start next year (2014) to allow SCC in drill shaft foundations. The 1500 coulombs permeability requirement reported in the table is only a required for mixture option 8 (less than 20% SCM replacement).

3.3.1.22 Virginia (VADOT)

The Virginia DOT reported they are using SCC mixes with little specification differences from normal concrete mix designs. The main differences are specifying a slump flow (ASTM 1611) rather than a slump, using the J-ring test (ASTM 1621) to check for flowability around steel and a different fine aggregate/coarse aggregate ratio. The specified SCC parameters are considered for general use.

3.3.1.23 Washington (WSDOT)

Washington State provided specification for precast elements which allows for SCC use. SCC is only used on a case-by-case basis for other applications and would have to meet the requirements for testing and submittals of that class of concrete. The Mix design parameters are the same for SCC as for conventional precast concrete. The aggregate size is limited either by intended use (form work and rebar spacing) or limits in specification by class of mix. In addition, they also specify the fresh performance parameters and the compressive strength for hardened performance.

3.3.1.24 West Virginia (WVDOT)

West Virginia reported they do not have a specification for the SCC in their standards. When SCC has been used, it has either been specified by special provision or on a case-by-case approval with direct coordination with the precast fabricator. West Virginia provided their special provision specifications that they used on projects in which prestressed concrete box beams, prestressed beams, and drilled shafts that were constructed with SCC.

3.3.2 Summary of the specifications

The information provided by the respondents are tabulated and provided in Tables 3.1 - 3.5. The respondents addressed the mixture parameters, fresh performance requirements, and the hardened performance requirements for SCC which are summarized below:

3.3.2.1 Mixture Parameters

Selection of the maximum and minimum cement contents depends on the overall requirements for concrete, such as strength and durability. Of the responding states, 75% (18 states) provided cement content requirements which is ranged between 470 -850 lb/yd3 for precast and 317 – 800 lb/yd3 for general use.

Of the states that responded 79% (19 states) allow fly ash, silica fume, and/or ground granulated blast furnace slag (GGBFS).

The maximum size of the aggregates depends on the particular application. Of the responding agencies, 62.5% (15 states) specify coarse aggregate gradation (maximum size or Nominal maximum size) limits, and about 46.7% of these agencies (7 of 15 states) specified ¾ inch as a maximum aggregate size.

The fine aggregate volume to total aggregate volume ratio is an important parameter for SCC. Eleven of the responding states (45.8%) provided a fine-to-total aggregate ratio limit, which is ranged between 0.4 to 0.5 for general use and 0.4 to 0.6 for precast use. In addition, 5 of the 11 (45.5%) states specified a 0.5 as a maximum fine-to-total aggregate ratio.

When a proper air-void system is provided SCC can exhibit excellent resistance to freezing and thawing cycles and to deicing salt scaling. Of the responding agencies, 18 (75%) specified ranges of air entrainment requirements, which ranged between 0 to 9%. In addition, 10 of 18 states (55.5%) reported 6.0± 1.5 % as air entrainment requirements.

Higher strengths in the SCC are generally achieved by lowering the water-cement ratio (w/c) of the concrete mixture. Of the respondents, 83.3% (20 states) addressed w/c limits, and 8 of the 20 (40%) specified 0.45 as a maximum w/c limit. Generally w/c ranged from 0.30 to 0.50 for both precast and general use.

3.3.2.2 Fresh Performance

SCC in its fresh state exhibits different characteristics than conventional concrete. SCC by definition must flow under its own weight without the need for mechanical vibration. In addition, it must exhibit filling ability, passing ability, and segregation stability, so that when

SCC consolidates it completely fill formwork and surround any steel reinforcement or prestressing strands.

The slump flow is the most widely used test to measure the filling ability of the SCC. Of the responding agencies, 19 (79.2%) specified a slump flow limits; it is ranged between 25 ±7in for general use and 26±3in for precast use.

The T50 is a method to quantify the flowing ability of SCC, and gives a relative index of the viscosity. The test measures the time for the concrete spread paddy to reach the 20 in. (50 cm). Seven states (29.1%) provided a T50 limits. Of these states, 4 out of 7 (57.1%) specified 2 to 7 sec for T50 test for the both precast and general use.

The Visual Stability Index (VSI) is a method for determining the stability of the mix and is determined through rating apparent stability of the slump flow patty. Of the responding agencies, 16 (66.7%) addressed a VSI limit, and 12 out of 16 agencies (75%) stated that a VSI of one or less would result in a stable batch.

The J-ring and L-Box are tests to measure the passing ability of SCC. The results show the J-ring is more commonly used by the responding states compared to L-Box test. The survey showed that 15 states (62.5%) are using the J-ring test, and 6 out of 15 states (40%) specified the difference between the conventional slump flow and the J-ring slump flow to be less than 2 inches for general use, and two states specified 3 inches as a difference for precast use. Also, 5 out of 15 states (33.3%) stated the J-ring slump flow to be less than 2 inch for the both general and precast use. Only one state (North Carolina) specified limits for the L-Box test which is 0.8 to 1.0 as the ratio of the height in the horizontal section relative to the vertical section.

Column segregation is a test to evaluate the static stability of a concrete mixture by quantifying aggregate segregation. Of the respondents, 10 states (41.6%) use this test to measure the stability of SCC, and 4 out of 10 states (40%) reported 10% as a maximum column segregation limit, and 3 out of 10 (30%) specified 15% as a maximum limit.

3.3.2.3 Hardened Performance

The Hardened properties of SCC may be engineered through the mixture proportion to be similar to those of a conventional concrete mixture. The hardened properties addressed in this survey are compressive strength (fc), modulus of elasticity (Ec), flexural/tensile strength, and permeability. Of the respondents, 17 (70.8%) states have compressive strength requirements and 9 states (37.5%) have permeability requirements. The average of minimum compressive strength ranged between 3,000 to 8,000 psi among the states, and the maximum current (permeability) ranged from 1500-3000 coulombs for general use and 1500-4000 coulombs for precast use. Modulus of elasticity and tensile strengths were not specified.

Table 3.1 Summary of State DOTs specifications of the mixture parameter for SCC Alabama - New Hampshire:

State	Type	Mixture Parameters						Notes
		Cement (lb/yd^3)	SCMS	Max Agg.	FA/TA	AE%	W/C	
AL	**Precast**	600-850	Fly Ash, GGBFS, Silica Fume	3/4 in	0.45 - 0.55	4 - 6	0.40 max	
AZ	**Precast**	715	Fly Ash, GGBFS, Silica Fume	½ in	0. 48 max	NS	0.40 max	
CA	**General**	NS	Fly Ash, GGBFS, UFFA, Metakaolin, Silica fume	2 in	NS	NS	NS	
CO	**Caissons**	610 min	Fly Ash	NS	0.50	8 max	0.38-0.45	
	Precast	NS	NS	NS	NS	NS	NS	
FL	**Precast**	470- 752 min	Fly Ash, GGBSF	NS	0.50 max	1- 6	0.45	
ID	**General**	560 min	Fly Ash, GGBFS, Silica Fume	NS	NS	6.5±1.5	Max 0.40 - 0.45	
KY	**Precast**	564 min	NS	NS	NS	6± 2	0.46 max	
ME	**Composite Arch Tube**	850 min	Fly Ash, GGBFS,	3/8 in	0.50 min	3 (±3)	0.43 max	Special provision
	General	660 max		NS	NS	7.50	NS	
MD	**Precast**	615 min	DC	DC	DC	6.5± 1.5	0.32-0.50	
MI	Not allowed							
MN	**Bridge**	NS	Fly ash GGBFS Silica Fume	NS	NS	6 ± 2	0.45 max	Special provision
MS	**General**	NS	Fly ash GGBFS	1 in	NS	3-6	0.45 max	
	Drilled Shafts	NS	Fly ash (F) GGBFS	¾ in	NS	NS	0.45 max	
NH	**Precast**	NS	NS	¾ in	NS	NS	0.45 max	

NS = not specified.

DC = as per design criteria.

Table 3.2 Summary of State DOTs specifications of the mixture parameter for SCC New Jersey - West Virginia

State	Type	Mixture Parameters						Notes
		Cement (Ib/yd)	SCMS	MAX agg	FA/TA	AE%	W/C	
NJ	**Drilled Shafts**	611	Fly Ash, GGBFS, Silica fume	3/8 in	0.5 max	7.5 ± 2.0	0.443	
	Precast	564 - 658					0.4	
NC	**Precast**	639 - 850	Fly Ash, GGBFS, silica fume,	NS	0.40- 0.60	6.0±1.5	0.48	Special provision
NV	**Drilled Shafts**	639-925	fly ash, silica fume, GGBFS	NS	0.57-0.43	4-7	0.4	Special provision
OR	Not allowed							
RI	**General**	400 – 700	Fly Ash, GGBFS, Silica Fume	3/4 in	NS	5 - 9	0.36 max	aggregate of 1.5 in. allowed by special provision
SC	No interest from industry or vendors							
SD	**General**	700-800	Fly Ash	3/4 in	0.55 max	5.0 -7.5	0.45 max	Special Provision
TX	**Precast**	700 max	Fly Ash, GGBFS, Silica fume, Metakaolin	1 in	NS	NS	0.45	
VA	**General**	423 - 800	Fly Ash (F), GGBFS, Silica fume, Metakaolin	NS	0.40-0.50	4 - 8	0.45	
WA	**Precast**	564 - 660	Fly Ash GGBFS	3/4 in	NS	4.5 - 7.5	NS	
WV	**Drilled Shafts**	566-752	Fly Ash(F), GGBFS, Silica fume, Metakaolin	3/4 in	0.50 max	4.5 -7.5	0.42	Special provision
	Precast	NS				4 - 6	0.42 max	Special provision

NS = not specified.
DC = as per design criteria.

Table 3.3 Summary of State DOTs specifications of the fresh performance for SCC Alabama - New Hampshire

State	Type	Fresh Performance				Notes
		Slump flow limits	T-50 sec	VSI	J-Ring/L-Box /column	
AL	**Precast**	27" ± 2"	NS	< 2.0	Δ slump flow J-Ring flow <3.0 in	
AZ	**Precast**	30" max	NS	< 2	Column Segregation under 8%	
CA	**General**	20"min	2 - 7	≤ 1	Δ slump flow J-Ring flow <2.0 in, Column Segregation< 15%, Bleeding Capacity < 2.5 %	
CO	**Caissons**	21" ± 3"	NS	NS	Δ slump flow J-Ring flow ≤ 2.0 in,	Static Segregation <10%
	Precast	NS	NS	NS	NS	NS
FL	**Precast**	27" ± 2.5"	2 - 7	≤ 1	Δ slump flow J-Ring flow <2.0 in, Column Segregation <15%	
ID	**General**	25" ± 7"	NS	1.5max.	Δ slump flow J-Ring flow ≤1.5 in, Column Segregation ≤10%	
KY	**Precast**	NS	NS	NS	NS	
ME	**Composite Arch Tube**	27" ± 3"	NS	1.5max.	NS	Special provision
	General	NS		0 - 1		
MD	**Precast**	25" ± 3"	6 ± 4	0 -1	J-ring Column segregation	
MI	Not allowed					
MN	**Bridge**	Max 28"	NS	≤ 1	NS	Special provision
MS	**General**	28" ±4"	NS	NS	Δ slump flow J-Ring flow <1.5 or 2.0 in, Column Segregation <15%, Bleeding capacity < 2.5 %	
	Drilled Shaft	21" ±3"	NS	NS	Column Segregation <10%	Special provision
NH	**Precast**	NS	NS	NS	NS	

NS = not specified.
DC = as per design criteria.

Table 3.4 Summary of State DOTs specifications of the fresh performance for SCC New Jersey - West Virginia

State	Type	Fresh Performance				Notes
		Slump flow limits	T-50 sec	VSI	J-Ring/L-Box /column	
NJ	**Drilled Shafts**	21" ± 3"	NS	≤ 1	NS	Special provision
	Precast	26" ± 2"	NS	≤ 1	NS	
NC	**Precast**	27" ± 3"	NS	NS	Δ slump flow J-Ring flow <3.0 in, L-box Ratio: 0.8 - 1.0	Special provision
NV	**Drilled Shafts**	23" ± 5"	NS	≤ 1	Δ slump flow J-Ring flow <2.0in	Special provisio
OR	Not allowed					
RI	**General**	23" ± 3""	NS	NS	Δ slump flow J-Ring flow <2.0 in	
SC	No interest from industry or vendors					
SD	**General**	25" ± 3"	NS	≤ 1	Δ slump flow J-Ring flow <2.0 in	
TX	**Precast**	25" ± 2"	2-7	0 or 1	Δ slump flow J-Ring flow ≤ 2 in, Column Segregation<10%, Bleeding < 2.5%	
VA	**General**	25 ± 3"	NS	0 or 1	Δ slump flow J-Ring flow <2.0 in	
WA	**Precast**	NS	< 6	≤ 1	Δ slump flow J-Ring flow ≤1.5 in, Column segregation <10%	
WV	**Drilled Shafts**	22" ± 1"	2 - 7	< 1.5	Δ slump flow J-Ring flow <1.5 in, Column Segregation <12%	Special provision
	Precast	23" ± 2"	2- 7	≤ 1	Δ slump flow J-Ring flow <1.5 in	Special provision

NS = not specified.
DC = as per design criteria.

Table 3.5 Summary of State DOTs specifications of the hardened performance for SCC Alabama - West Virginia

State	Type	Hardened Performance				Notes
		f´c (psi) 28 day	flexural /tensile	Ec(ksi)	Permeability (coulombs)	
AL	**Precast**	5000	NS	NS	Max 2,000	Permeability requirement for marine environments
AZ	**Precast**	DC	NS	NS	NS	
CA	**General**	DC	NS	NS	NS	
CO	**Caissons**	4000	NS	NS	NS	
	Precast	DC	NS	NS	NS	
FL	**Precast**	3000 - 8500	NS	NS	NS	
ID	**General**	3000-3500	NS	NS	NS	
KY	**Precast**	3500	NS	NS	NS	
ME	**Composite Arch Tube**	6000	NS	NS	NS	Special provision
	General	4350-5075	NS	NS	2000 - 2400	
MD	**Precast**	DC	NS	NS	2500	
MI	Not allowed					
MN	**Bridge**	4300	NS	NS	NS	Special provision
MS	**General**	4000	NS	NS	NS	
	Drilled Shaft		NS	NS	NS	Special provisions
NH	**Precast**	DC	NS	NS	NS	
NJ	**Drilled Shaft**	4600	NS	NS	NS	Special provision
	Precast	5400 min	NS	NS	max 1000	
NC	**Precast**	NS	NS	NS	NS	Special provision
NV	**Drilled Shaft**	4000	NS	NS	NS	Special provision
OR	Not allowed					
RI	**General**	3000 - 5000	NS	NS	1500 -3000	
SC	No interest from industry or vendors					
SD	**General**	4500 min	NS	NS	NS	
TX	**Precast**	DC	NS	NS	<1500	
VA	**General**	DC	NS	NS	NS	
WA	**Precast**	DC	NS	NS	NS	
WV	**Drilled Shaft**	4500 min	NS	NS	NS	Special provision
	Precast	8000	NS	NS	1500	Special provision

NS = not specified.
DC = as per design criteria.

CHAPTER 4

EXPERIMENTAL PLAN

4.1 Introduction

Throughout this chapter, the mixtures proportions, materials and suppliers, and the fresh tests used in the experimental program are discussed. As mentioned in the first chapter This study is part of the proposed project by Tennessee Department of Transportation (TDOT) carried out by University of Tennessee at Chattanooga (UTC) to develop four new SCC mixtures (two Class P-SCC (precast) and two Class A-SCC (general use)), and insure they meet the minimum strength and durability requirement for TDOT Class P and Class A mixtures. Throughout this study, only the Class A (general use) mixtures were selected for detailed studies of their fresh properties. Therefore the development of the Class P (precast) mixtures is out of the scope of this study.

During this project the survey of state Departments of Transportation (DOTs) was conducted to gather specifications related to SCC use for general and precast elements in other states. The survey addressed the mixture parameters, fresh performance requirements, and the hardened performance requirements. The findings of the survey were used to develop and select the mixture proportions and components, and selecting the appropriate methods to evaluate the fresh characteristics of Class A SCC mixtures. In accordance with the requirements of this project, the materials used in the study were procured from local suppliers within the state of Tennessee and are TDOT approved materials.

4.2 Mix Designs

The mixture parameters used by other states were analyzed and the mix designs for Class A concrete (general use) were then established according to the other states specifications, and TDOT Class A requirements. A total of 24 mixtures were developed which represent two Class A-SCC mixtures and some conventional concrete as control mixtures.

The Class A mixtures were designed with 20% cement replacement using Class C fly ash for one mixture, and Class F for the other. Each Class A mixtures was duplicated 12 times with varying visual stability index values of 1 and 2, different aggregate sizes (ASTM C 33 #57,#67, and # 7), and with natural and manufactured sand as shown in Tables 4.1 and 4.2. Different HRWR dosages were used to provide different fresh properties and to achieve the high flowability of the SCC without increasing the w/cm. Typically, the mixtures were designed with HRWR dosages of 7 oz/cwt and 9 oz/cwt to to provide a VSI of 1 and 2 respectively, and dosage of 4 oz/cwt of mid-range water reducer to provide conventional concrete mixtures with a slump of 3 to 5.5 in.. HRWR doses were later adjusted and corrected during the mixing to attain the desirable fresh properties. SCC mixtures were designed with 50% sand to total volume to provide the necessary filling, passing, and flowability characteristics, and a 44% sand ratio was used for conventional concrete mixtures. Typically, all the mixtures were designed with 0.45 water cementation materials ratio. In addition, the TDOT Class A mixtures were developed to have a 6% air entertained using Air entrained admixtures (AEA) to provide the necessary durability of SCC. Mixture proportions of the experiential mixtures are provided in Tables 4.1 and 4.2. The aggregate weights are provided for the saturated-surface dry condition.

Table 4.1 TDOT Class A mixtures with 20% cement replacement of Class C fly ash

Mixture No	25	26	27	28	29	30	31	32	33	34	35	36
VSI	1	2	Con.	1	2	Con.	1	2	Con.	1	2	Con.
Cement	496	496	496	496	496	496	496	496	496	496	496	496
Class F-Ash	0	0	0	0	0	0	0	0	0	0	0	0
Class C-Ash	124	124	124	124	124	124	124	124	124	124	124	124
# 57 stone	1504	1504	1684	0	0	0	0	0	0	0	0	0
# 67 stone	0	0	0	1504	1504	1684	1504	1504	1684	0	0	0
# 7 stone	0	0	0	0	0	0	0	0	0	1504	1504	1684
Natural sand	1426	1426	1256	1426	1426	1256	0	0	0	1426	1426	1256
Manufactured sand	0	0	0	0	0	0	1504	1504	1324	0	0	0
Design Air	6%	6%	6%	6%	6%	6%	6%	6%	6%	6%	6%	6%
Water	279.1	279.1	279.1	279.1	279.1	279.1	279.1	279.1	279.1	279.1	279.1	279.1
AEA (oz/yd)	2	2	2	2	2	2	2	2	2	2	2	2
H/MRWR (oz/cwt)	7	9	4	7	9	4	7	9	4	7	9	4
w/cm ratio	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45
Sand ratio by volume	0.50	0.50	0.44	0.50	0.50	0.44	0.50	0.50	0.44	0.50	0.50	0.44

All weights in lbs./yd^3.
HRWR and AEA dosages are design values, the actual values are shown in Chapter 5.
Admixture demands are dependent on aggregates.
Con.: Conventional concrete.

Table 4.2 TDOT Class A mixtures with 20% cement replacement of Class F fly ash

Mixture No	37	38	39	40	41	42	43	44	45	46	47	48
VSI	1	2	Con.	1	2	Con.	1	2	Con.	1	2	Con.
Cement	496	496	496	496	496	496	496	496	496	496	496	496
F-Ash	124	124	124	124	124	124	124	124	124	124	124	124
C-Ash	0	0	0	0	0	0	0	0	0	0	0	0
# 57 stone	1504	1504	1684	0	0	0	0	0	0	0	0	0
# 67 stone	0	0	0	1504	1504	1684	1504	1504	1684	0	0	0
# 7 stone	0	0	0	0	0	0	0	0	0	1504	1504	1684
Natural sand	1426	1426	1256	1426	1426	1256	0	0	0	1426	1426	1256
Manufactured sand	0	0	0	0	0	0	1504	1504	1324	0	0	0
Design Air	6%	6%	6%	6%	6%	6%	6%	6%	6%	6%	6%	6%
Water	279.1	279.1	279.1	279.1	279.1	279.1	279.1	279.1	279.1	279.1	279.1	279.1
AEA (oz/yd)	2	2	2	2	2	2	2	2	2	2	2	2
H/M-RWR (oz/cwt)	7	9	4	7	9	4	7	9	4	7	9	4
w/cm ratio	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45
Sand ratio by volume	0.50	0.50	0.44	0.50	0.50	0.44	0.50	0.50	0.44	0.50	0.50	0.44

All Weights in lbs. /yd^3.
HRWR and AEA dosages are design values, the actual values are shown in Chapter 5.
Admixture demands are dependent on aggregates.
Con.: Conventional concrete

4.3 Materials Used in The Experimental Plan

4.3.1 Powders

4.3.1.1 Cement

The cement type used in this study was an ASTM C 150 Type I. Enough cement was procured locally from Buzzi Unicem USA- Chattanooga, TN Plant for the entire project. The stock was stored in the laboratory during the study period. The chemical composition of the cement is shown in Table 4.3.

Table 4.3 The chemical composition of the cement.

Component	**Weight %**	**Component**	**Weight %**
SiO_2	19.8	C_3S	64.1
Al_2O_3	4.6	C_2S	8.3
Fe_2O_3	3.5	C_3A	6.2
CaO	63.3	C_4AF	10.7
MgO	3	C_3S+4.75C_3A	93.3
SO_3	2.7	CO_2	1.2
Total alkalis(Na_2O +0.658 K_2O	0.53	Limestone	3.1
Ignition Loss	1.7	$CACO_3$ in Limestone	89.2
Insoluble Residue	0.3	-	-

4.3.1.2 Fly ash

Two types of fly ash were used during this study; ASTM C 618 Classes C and F. Fly ash was used to replace 20 % of portland cement in the mixtures. Enough Class F fly ash sourced locally from The SEFA Group Cumberland City, TN for the entire project, and was kept in the laboratory during the study period. Enough Class C fly ash sourced from Plant Miller, GA. The chemical composition of Class F and C fly ash are shown in Table 4.4 and 4.5 respectively.

Table 4.4 The chemical composition of Class F fly ash.

Component	Weight %
SiO_2	44.29
Al_2O_3	18.39
Fe_2O_3	19.23
Sum of Constituents	81.9
CaO	8.87
MgO	0.86
SO_3	2.72
Loss on Ignition	1.65
Moisture Content	0.16
Available Alkalis as Na_2O	0.84

Table 4.5 The chemical composition of Class C fly ash.

Component	Weight %
SiO_2	37.58
Al_2O_3	18.39
Fe_2O_3	6.15
Sum of Constituents	62.12
SO_3	1.88
CaO	24.41
MgO	5.58
Na_2O	1.82
K_2O	0.58
Moisture	0.13
Loss on Ignition	0.51
Available Alkalis, as Na_2O	1.49

4.3.2 Coarse Aggregates

The coarse aggregates employed in this study were crushed stone type, sourced locally from Vulcan Materials, Chattanooga, TN. Different aggregate sizes were used during this study which includes ASTM C 33 #57 Stone, #67 Stone, and #7 Stone, and all met TDOT standards. All the coarse aggregates had bulk specific gravity of 2.74 and absorption of 0.62 %. Tables 4.6, 4.7, and 4.8 show the coarse aggregate grading for #57 Stone, #67 Stone, and #7 Stone respectively, and the combined aggregate graduation is shown in Figure 4.1.

Table 4.6 #57 Stone gradation

Sieve Opening	Cumulative Percent Passing
1.25 in.	100%
1 in.	95%
¾ in.	76%
½ in.	42%
3/8 in.	26%
NO. 4	6%
Pan	0%

Table 4.7 #67 Stone gradation

Sieve Opening	Cumulative Percent Passing
1 in.	100%
¾ in.	90%
½ in.	51%
3/8 in.	35%
NO. 4	8%
Pan	0%

Table 4.8 #7 Stone gradation

Sieve Opening, inch	Cumulative Percent Passing
¾ in.	100%
½ in.	99%
3/8 in.	80%
NO. 4	11%
NO. 8	1%
Pan	0%

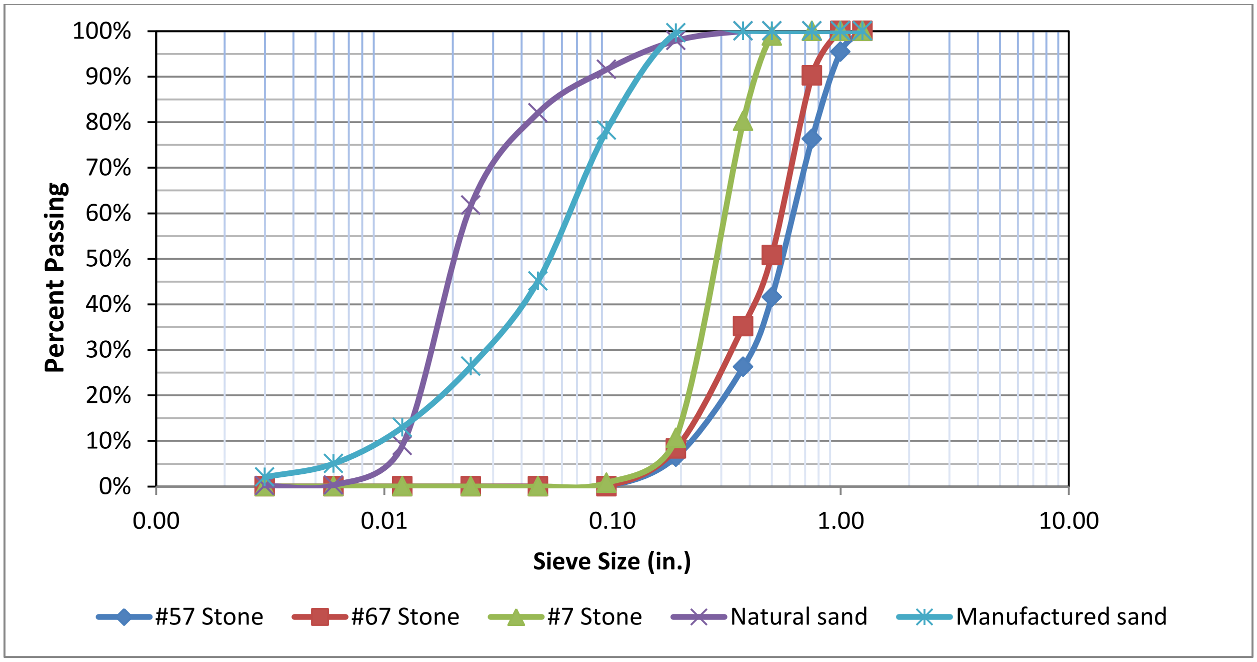


Figure 4.1 The combined aggregate gradation

4.3.3 Fine Aggregates

Two types of fine aggregate were used in this study; natural and manufactured sand, the both meet the TDOT standards. The natural sand (River sand) was sourced locally from Pine Bluff Materials, Nashville, TN**.** The bulk specific gravity of the natural sand was 2.6 and the absorption was 1.30 %. The manufactured sand was also sourced locally from Vulcan Materials, Chattanooga, TN, which has bulk specific gravity of 2.74 and absorption of 0.64 %. The natural and manufactured sand gradations are shown in Tables 4.9 and 4.10 respectively, and their graduations are shown in Figure 4.1.

Table 4.9 Natural sand gradation

Sieve Opening	Cumulative Percent Passing
3/8 in.	100.0%
NO. 4	97.9%
NO. 8	91.6%
NO. 16	82.0%
NO. 30	61.8%
NO. 50	9.0%
NO. 100	0.3%
NO. 200	0.1%
Pan	0.0%

Table 4.10 Manufactured sand gradation

Sieve Opening	Cumulative Percent Passing
3/8 in.	100.0%
NO. 4	99.6%
NO. 8	78.2%
NO. 16	45.1%
NO. 30	26.4%
NO. 50	13.0%
NO. 100	5.0%
NO. 200	2.0%
Pan	0.0%

4.3.4 Chemical Admixtures

4.3.4.1 Mid-Range Water-Reducing Admixture

MasterPolyheed 900 is a Mid-Range Water-Reducing Admixture that was used to improve the workability of conventional concrete mixtures, to attain a 4 in slump without increasing the water cement ration. MasterPolyheed 900 admixture meets ASTM C 494/C 494M requirements for Type A, water-reducing admixtures. It was sourced from the BASF Corporation. Its technical data sheet that was obtained from the supplier is summarized in Table 4.11.

Table 4.11 Technical Data of MasterPolyheed 900

Data	**Specification**
Initial Set time (hr:min)	5:18
Water reduction	9 - 10 %
Storage Temperature	35 to 105 °F
Minimum shelf life	18 months
Recommended dosage range	3 to 15 fl oz/cwt of cementitious materials

4.3.4.2 Full -Range Water-Reducing Admixture

MasterGlenium 7500 is a Full -Range Water-Reducing Admixture that was used to produce SCC mixtures with different levels of flowability, without increasing the water cement ratio. MasterGlenium 7500 admixture meets ASTM C 494C/ 494M compliance requirements for Type A, water-reducing, and Type F, high-range water-reducing admixtures. It was also sourced from the BASF Corporation. Its technical data sheet obtained from the supplier is summarized in Table 4.12.

Table 4.12 Technical Data of MasterGlenium 7500

Data	**Specification**
Water reduction	5 - 40%
Storage Temperature	above 40 °F
Minimum shelf life	9 months
Recommended dosage range	2 to 15 fl oz/cwt of cementitious materials

4.3.4.3 Air-Entraining Admixture

MasterAir AE 90 is an air-entraining admixture, was use to provide a uniform structure of voids in concrete mixtures; in order to improve its resistance to damage from cyclic freezing and thawing. MasterAir AE 90 meets the requirements of ASTM C 260, AASHTO M 154 and CRD-C 13. It was sourced from the BASF Corporation. The exact dosage of air-entraining admixture needed for the 6% air content of concrete varied between the mixtures, and it was adjusted during the trial batching process. MasterAir AE 90 technical data sheet obtained from the supplier and summarized in Table 4.13.

Table 4.13 Technical Data of MasterAir AE 90

Data	**Specification**
Water reduction	5 - 40%
Storage Temperature	31 °F (-0.5 °C) or higher
Minimum shelf life	18 months
Trial mixture recommended dosage range	0.25 to 4 fl oz/cwt of cementitious materials

4.3.5 Mixing water

Municipal tap water was used throughout the experimental mixtures. The average water temperature was 70 +/- 2 °F.

4.4 Preparation of The Experimental Mixes

During this study, TDOT Class A (General use) mixes were selected for detailed studies of their fresh properties. Typically, a batch of four and a half cubic feet was prepared to provide concrete for the fresh and hardened property test samples of the SCC, and only three cubic feet of conventional concrete was required. Conventional concrete required a smaller batch due to the fewer fresh tests than the SCC.

Coarse and fine aggregate were stock piled outside the Laboratory area. Aggregate moisture corrections were used to adjust the batch components (water and aggregates) before mixing to account for moisture condition of the aggregates. The moisture content of aggregate was calculated after weighing a representative sample from the aggregate pile before and after drying it using an electric heater. Appropriate weights of components (4.5 ft^3 of SCC, or 3 ft^3 of conventional concrete) were measured, adjusted, and then added together in the six cubic foot electric drum-type mixer. Firstly, the coarse and fine aggregates were added together and mixed for one minute with 75% of the required water. The water contained the AEA if needed. The cement and fly ash were then added to the stopped mixer and mixed for three minutes with the remaining mixing water which was added gradually while the mixer was running, followed by three minutes rest, and followed by two minutes final mixing. The high range water reducing admixture was added gradually while the mixer was running. After thorough mixing, the mixture was ready for taking the samples for fresh and hardened property tests of SCC and conventional concrete, as outlined in the testing protocol in Tables 4.14 and 4.15.

Table 4.14 Testing Protocol of SCC mixtures

Fresh Concrete Testing	
Slump Flow and Visual Stability Index (ASTM C 1611)	1 per batch
Consolidating ability by J-Ring (ASTM C 1621)	1 per batch
Static Segregation by Column Test (ASTM C 1610)	1 per batch
Unit Weight and Gravimetric Air Content (ASTM C 138)	1 per batch
Air Content by Pressure Method (ASTM C 231)	1 per batch
Time of setting of Concrete Mixtures by Penetration Resistance (ASTM C 403)	1-6.5*6.5 inch cylinder per batch
Hardened Concrete Testing	
Compressive Strength [1] (ASTM C 39)	2-6x12 inch cylinders per test time
Static Modulus of Elasticity[1] (ASTM C 469)	The 2-6x12 compressive strength cylinders will also be used for modulus per test time
Splitting Tensile Strength [1](ASTM C 496)	2-6x12 inch cylinders per test time

[1] The hardened properties will be tested at 7 days only.

Table 4.15 Testing Protocol of conventional concrete mixtures

Fresh Concrete Testing	
Slump Flow (ASTM C 143)	1 per batch
Unit Weight and Gravimetric Air Content (ASTM C 138)	1 per batch
Air Content by Pressure Method (ASTM C 231)	1 per batch
Time of setting of Concrete Mixtures by Penetration Resistance (ASTM C 403)	1-6.5*6.5 inch cylinder per batch
Hardened Concrete Testing	
Compressive Strength [1] (ASTM C 39)	2-6x12 inch cylinders per test time
Static Modulus of Elasticity[1] (ASTM C 469)	The 2-6x12 compressive strength cylinders will also be used for modulus per test time
Splitting Tensile Strength [1](ASTM C 496)	2-6x12 inch cylinders per test time

[1] The hardened properties will be tested at 7 days only.

4.5 Fresh Property Tests on The Experimental Mixes

The main objectives of this study are to investigate the fresh characteristics and the fresh segregation potential of SCC mixtures. Several methods were used to test the fresh properties and characteristics of SCC, which are briefly described below:

4.5.1 Slump Flow Test

The main apparatus for this test was the conventional cone which has 8 in base diameter, 4 in top diameter, and 12 in height. The cone was filed with fresh SCC, while firmly holding the cone on the center of damped base plate, with the smaller opening facing down. The top of the cone was stuck off using the strike-off bar to remove any excess materials. The cone was gently raised vertically in about four seconds, forming a patty. After the concrete stopped flowing the largest diameter of the patty was measured in two perpendicular directions. The average value of the two diameters was recorded as the slump flow diameter. The range of slump flow was kept between 18 to 30 inches (450 to 760 mm) for SCC as recommended by ACI Committee 237. Figure 4.2 shows the slump flow test.

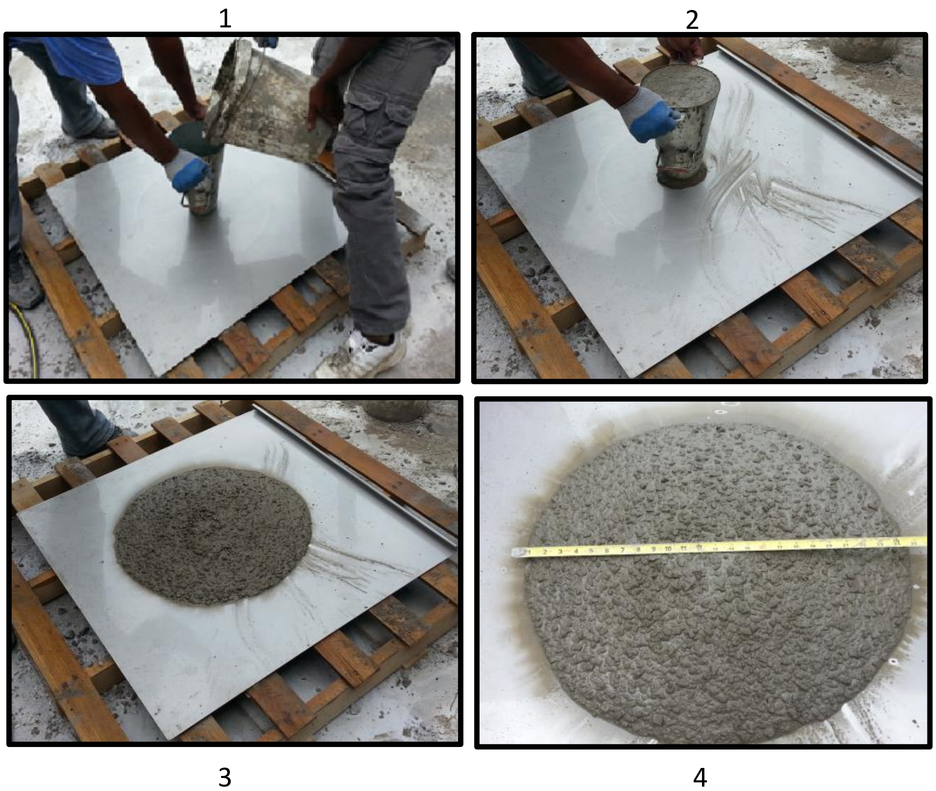
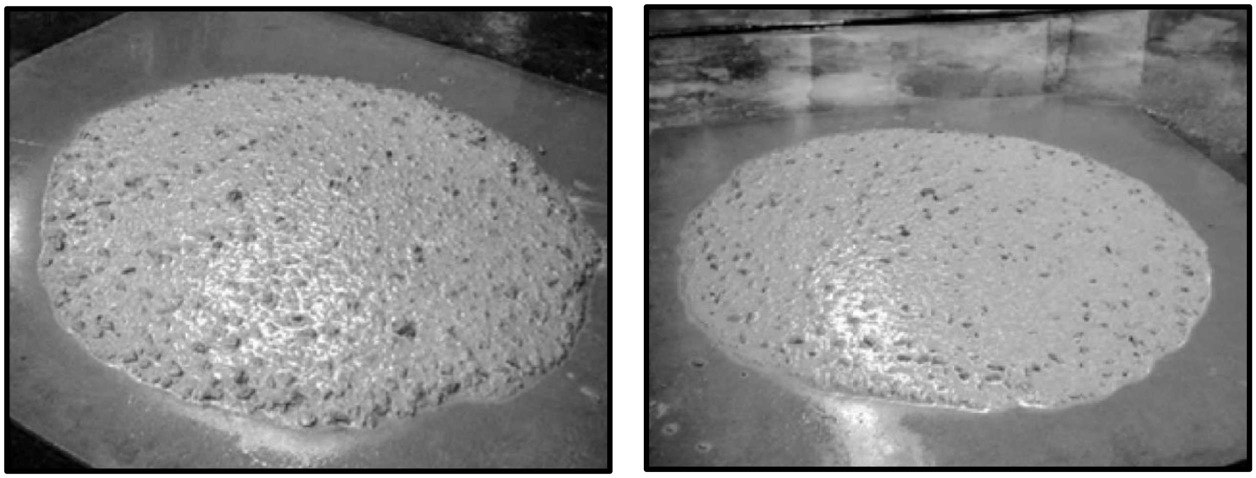


Figure 4.2 The slump flow test

4.5.2 Visual Stability Index

The VSI was determined through visually rating the apparent stability of the slump flow patty based on specific visual properties of the spread patty. The SCC mixtures were designed with a VSI of 1 and 2 which illustrates a stabilized and segregated mixtures respectively. The desirable VSI values were achieved during mixing by HRWR dosages. Assigning the VSI values (1 or 2) to the concrete spread was conducted using the criteria shown in Figure 4.3 (ASTM C1611C1611M).



VSI = 1 – No evidence of segregation and slight bleeding observed as a sheen on the concrete mass

VSI = 2 – A slight mortar halo # 0.5 in.(# 10 mm) and/or aggregatepile in the of the concrete mass

Figure 4.3 Visual stability index criteria

4.5.3 T50

The T50 value was measured during the slump flow test to quantify the flowing ability of SCC, and to provide a relative index of the viscosity. During the slump flow test, the time for the concrete paddy to reach a diameter of 20 in (50 cm) from the time the cone was first lifted was measured in seconds using a stopwatch, as shown in Figure 4.4.

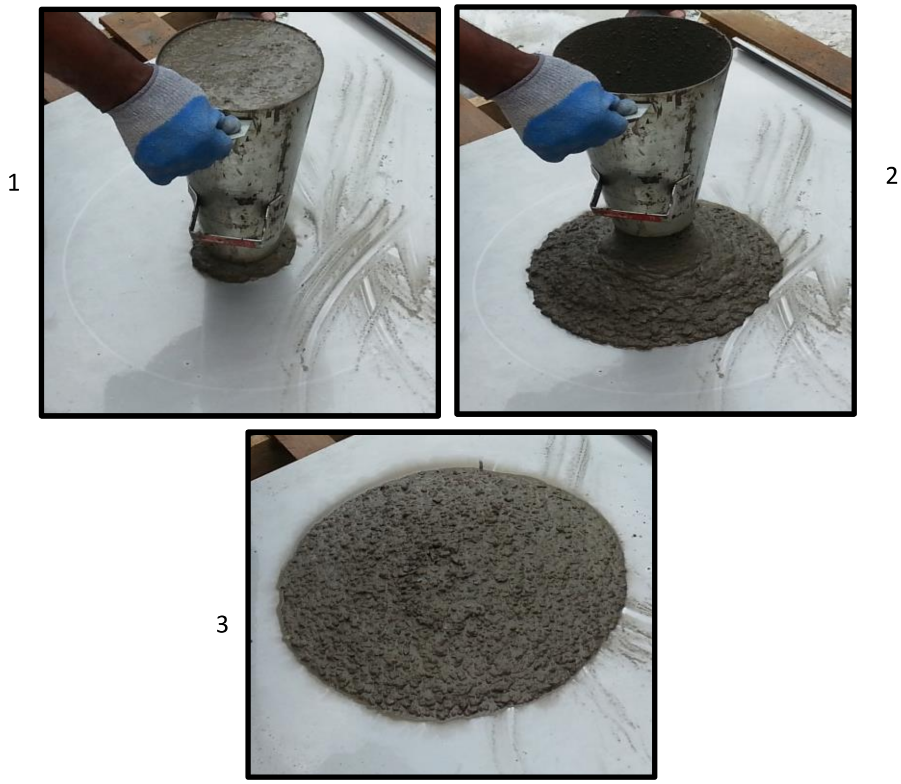


Figure 4.4 T50 measurement

4.5.4 J-ring test

A sample of fresh SCC was poured in a moistened standard slump cone with the J-ring base which contains steel bars. The cone was firmly held on the center of damped base plate with the smaller opening facing down. Then the top of the cone was stuck off using the strike-off bar to remove the excess materials. The mold was then raised, the SCC passed through J-ring, and the average of diameters measured in two perpendicular directions was recorded as the J-ring flow diameter. An example of a J-Ring test is shown in Figure 4.5.

Figure 4.5 J-ring Test

4.5.5 L-box test

L-Box test was used to evaluate the passing ability of the SCC mixtures. The SCC was poured in the vertical section to its full height; the top of the section was struck off using the strike-off bar, to remove any excess materials. The gate was then lifted to allow the concrete to flow into the horizontal section. When the flow stopped, the heights of the concrete were measured at the end of the horizontal section and in the vertical section. The ratio of the height of concrete in the horizontal section to remaining in the vertical section was recorded. An example of L-Box testing is shown in Figure 4.6.

1 2

3 4

Figure 4.6 L-box test

4.5.6 Column Segregation

Column Segregation was used to assess the fresh segregation resistance of SCC. A sample of freshly SCC was poured in one lift in the cylindrical column without tapping or vibration. After 15 minutes the column sections were separated using a cutting plate. The SCC from the top and bottom sections was collected and washed through a No.4 (4.75 mm) sieve, leaving the coarse aggregate on it. The coarse aggregate from the top and the bottom levels of the column were brought to the surface-dry condition by rolling them in a dry towel. The weights of the aggregates were determined in order to calculate the percentage of segregation using equation 4.1. An example of the column segregation test apparatus is shown in Figure 4.7

$$S = 2\left[\frac{(CA_B - CA_T)}{(CA_B + CA_T)}\right] * 100\ , if\ CA_B > \ CA_T\ \ldots. \quad \text{Equation 4.1}$$

$$S = 0, if CA_B \leq \ CA_T$$

Where:

S = static segregation, percent.

CA_T = mass of coarse aggregate in the top section of the column.

CA_B = mass of coarse aggregate in the bottom section of the column.

Figure 4.7 The static column segregation

4.5.7 Unit Weight of fresh concrete

This test was conducted to determine the density of freshly mixed concrete, in accordance with the ASTM C 138 standard. The main apparatus is a cylindrical container made of steel with 8 in diameter and 8.5 in height. The conventional concrete was placed in three layers using a scoop. Each layer was rodded 25 times with a tamping rod, and then the sides of the measure were tapped about 10 times using rubber mallet. The top of the mold was then stuck off using the strike-off bar, to remove excess materials. The mass of the mold and concrete were then determined, and the density was calculated using the equation 4.2. Same method was used for the SCC mixtures, but the concrete was poured in one layer without rodding or tapping.

$$D = \frac{M_c - M_m}{V_m} \text{ ……..Equation 4.2}$$

Where:

D = density (unit weight) of concrete, lb/ft^3

M_c = mass of the measure filled with concrete, lb

M_m = mass of the measure, lb

4.5.8 Air Content by Pressure Method

This method was used to determine the air content of freshly mixed concrete through the observation of the change in volume of concrete with a change in pressure, in accordance with the ASTM C 231 standard. The main apparatus is a Meter type B which consists of cylindrical container made of steel with 8 in diameter and 8.5 in height, and a cover assembly which is fitted with a pressure gauge, air valves, and petcocks for bleeding off. The conventional concrete was placed in three layers using a scoop. Each layer was rodded with 25 stokes of a tamping rod, then the sides of the measure were tapped 10-15 times using rubber mallet. The top of the mold was then stuck off using the strike-off bar, to remove the excess materials. After that, the cover assembly was placed and clamped, the main air valve was closed, and both the petcocks thought the cover were opened. Clean water was injected through one petcock until the water emerged from the other petcock with no bubbles. After that, the air bleeder valve was closed, and the air was pumped into the air chamber until the gauge reached the initial pressure line. Eventually, the main air valve was released, and the percentage of air was read on the dial of the pressure gauge. The same method was used for the SCC mixtures; however the SCC was poured in one layer without rodding or tapping. An example of the air content measurement is shown in Figure 4.8

Figure 4.8 Air content test

CHAPTER 5

RESULTS AND DISCUSSION

5.1 Introduction

Throughout this chapter, the results of the fresh property tests and the seven-day compressive strength, splitting tensile strength, and the concrete elastic modulus are presented, for the 24 mixtures conducted during this study. The correlations between these mixtures using different aggregate sizes (#57 stone, #67 stone, and #7 stone, natural and manufactured sand) and fly ash classes (C and F) are presented and discussed. Since the main objective of this study is to investigate the relationship between VSI and segregation potential of SCC mixtures, an assortment of graphs have been produced to represent the effects of VSI of 1 and 2, using Class F and C fly ash , on the fresh properties of the mixtures

5.2 Mixture Properties

Using Class A (general use) mixture proportions represented in Tables 4.1 and 4.2 in Chapter 4, a total of 24 mixtures, comprised of SCC and conventional concrete, were developed with different fresh properties and characteristics. SCC mixtures were produced with VSI values of 1 and 2, to achieve varying degrees of fresh characteristics such as filling ability, passing ability, and stability. Conventional concrete mixtures were developed, as control mixtures for SCC, with a slump range of 3 to 5.5 in. The fresh and seven-day hardened properties, including slump flow, density, air content, T50, VSI, J-ring, L-Box, column segregation, initial and final set time, compressive strength, tensile splitting strength, and concrete elastic modulus, are represented in Tables 5.1 to 5.8, for the different aggregate sizes (#57 stone, #67 stone, and #7 stone) and fly ash Class C and F. Table 5.1 provides the results of the testing for the mixture with #57 stone, natural sand and Class C fly ash. Table 5.2 shows the results of the testing for the mixture with #57 stone, natural sand and Class F fly ash. Tables 5.3 and 5.4 represent the results for the mixture with #67 stone and natural sand with fly ash Class C and F respectively. The results of the testing for the mixture with #67 stone and manufactured sand are represented in Tables 5.5 and 5.6 for fly ash Class C and F respectively. Table 5.7 shows the results of the mixture with #7 stone, natural sand and Class F fly ash, and Table 5.8 represents the results of the mixture with #7 stone, natural sand and Class C fly ash.

Table 5.1 Test results for #57 Aggregate + Natural Sand + C Ash mixture

Fresh properties									
Mix No	**Type**	**Slump (in.)**	**Temp (F.)**	**Air Content (%.)**	**Unit.Wt lbs/ft^3**	**T-50 (sec.)**	**VSI**	**J-Ring (in.)**	**L-Box ratio**
25	SCC	26.25	74	6.5%	138.4	0.9	1	23	0
26	SCC	29.25	76	6.0%	139.6	0.43	2	28.25	0.75
27	Conv.	4	67	6.7%	141	-	-	-	-
Fresh properties							**7-Day hardened properties**		
Mix No	**Type**	**Column segregation**	**AEA (oz/yd^3)**	**HRWR (oz/cwt)**	**Init.set (hr:min)**	**Fin.set (hr:min)**	**Fc (psi)**	**Splitting (psi)**	**E (Ksi)**
25	SCC	8.14%	1.8	5.8	5:30	7:10	5000	380	4550
26	SCC	19.42%	1.4	6.5	6:00	7:45	5370	405	5050
27	Conv.	-	7.5	0.0	5:15	7:00	4540	370	4500

Table 5.2 Test results for #57 Aggregate + Natural Sand + F Ash mixture

Fresh properties									
Mix No	**Type**	**Slump (in.)**	**Temp (F.)**	**Air Content (%.)**	**Unit.Wt lbs/ft^3**	**T-50 (sec.)**	**VSI**	**J-Ring (in.)**	**L-Box ratio**
38	SCC	24.5	82	6.0%	139.2	2.25	1	22.75	0
37	SCC	26	80	5.2%	140	0.75	2	25.5	0.75
39	Conv.	5.5	68	5.6%	142	-	-	-	-
Fresh properties							**7-Day hardened properties**		
Mix No	**Type**	**Column segregation**	**AEA (oz/yd^3)**	**HRWR (oz/cwt)**	**Init.set (hr:min)**	**Fin.set (hr:min)**	**Fc (psi)**	**Splitting (psi)**	**E (Ksi)**
38	SCC	11.26%	2.0	4.8	6:00	7:43	4150	345	4250
37	SCC	16.67%	2.2	5.8	7	8:42	3870	330	4850
39	Conv.	-	7.5	0.0	5:36	7:35	4360	325	4900

Table 5.3 Test results for #67 Aggregate + Natural Sand + C Ash mixture

Fresh properties									
Mix No	Type	Slump (in.)	Temp (F.)	Air Content (%.)	Unit.Wt lbs/ft^3	T-50 (sec.)	VSI	J-Ring (in.)	L-Box ratio
28	SCC	24.5	82	7.2%	136	1:47	1	23.5	0
29	SCC	29.5	79	6.0%	137	1:44	2	27.75	0.59
30	Conv.	4.25	75	5.4%	141	-	-	-	-
Fresh properties							**7-Day hardened properties**		
Mix No	**Type**	**Column segregation**	**AEA (oz/yd^3)**	**HRWR (oz/cwt)**	**Init.set (hr:min)**	**Fin.set (hr:min)**	**Fc (psi)**	**Splitting (psi)**	**E (Ksi)**
28	SCC	5.0%	1.6	4.2	6:00	7:51	4800	340	4400
29	SCC	7.0%	1.6	5.8	6:42	8:08	4500	395	4350
30	Conv.	-	3.0	0.0	4:50	6:45	5280	430	5150

Table 5.4 Test results for #67 Aggregate + Natural Sand + F Ash mixture

Fresh properties									
Mix No	Type	Slump (in.)	Temp (F.)	Air Content (%.)	Unit.Wt lbs/ft^3	T-50 (sec.)	VSI	J-Ring (in.)	L-Box ratio
40	SCC	27.5	81	6.0%	139	1:09	1	26.75	0.89
41	SCC	28.375	78	5.2%	140	0:40	2	27.0625	0.76
42	Conv.	3	76	6.0%	141	-	-	-	-
Fresh properties							**7-Day hardened properties**		
Mix No	**Type**	**Column segregation**	**AEA (oz/yd^3)**	**HRWR (oz/cwt)**	**Init.set (hr:min)**	**Fin.set (hr:min)**	**Fc (psi)**	**Splitting (psi)**	**E (Ksi)**
40	SCC	10.5%	2.0	6.5	6:12	7:53	4450	365	4500
41	SCC	14.1%	3.2	7.4	6:55	8:36	3580	250	4350
42	Conv.	-	7.5	0.0	5:30	7:30	4190	355	3350

Table 5.5 Test results for #67 Aggregate + Manufactured Sand + C Ash mixture

Fresh properties									
Mix No	**Type**	**Slump (in.)**	**Temp (F.)**	**Air Content (%.)**	**Unit.Wt lbs/ft^3**	**T-50 (sec.)**	**VSI**	**J-Ring (in.)**	**L-Box ratio**
31	SCC	22	73	5.1%	141	2:25	1	19	0
32	SCC	28.5	75	5.4%	137	1:50	2	26.5	0
33	Conv.	5.5	72	5.7%	140		-	-	-
Fresh properties							**7-Day hardened properties**		
Mix No	**Type**	**Column segregation**	**AEA (oz/yd^3)**	**HRWR (oz/cwt)**	**Init.set (hr:min)**	**Fin.set (hr:min)**	**Fc (psi)**	**Splitting (psi)**	**E (Ksi)**
31	SCC	12.3%	0.8	5.3	4:54	6:36	5180	435	4500
32	SCC	14.1%	1.6	5.8	5:20	7.15	4180	440	4100
33	Conv.	-	3.0	0.0	5:18	7:15	4660	335	4600

Table 5.6 Test results for #67 Aggregate + Manufactured Sand + F Ash mixture

Fresh properties									
Mix No	**Type**	**Slump (in.)**	**Temp (F.)**	**Air Content (%.)**	**Unit.Wt lbs/ft^3**	**T-50 (sec.)**	**VSI**	**J-Ring (in.)**	**L-Box ratio**
43	SCC	24.5	78	6.2%	137	2.91	1	21.75	0
44	SCC	27.38	73	5.7%	140	1.81	2	26	0.1
45	Conv.	3	76	6.0%	143.4	-	-	-	-
Fresh properties							**7-Day hardened properties**		
Mix No	**Type**	**Column segregation**	**AEA (oz/yd^3)**	**HRWR (oz/cwt)**	**Init.set (hr:min)**	**Fin.set (hr:min)**	**Fc (psi)**	**Splitting (psi)**	**E (Ksi)**
43	SCC	9.0%	2.0	6.8	4:30	6:06	4280	440	4350
44	SCC	10.3%	0.8	8.9	5:40	7:12	4580	395	4450
45	Conv.	-	3.0	4.1	5:00	6:30	4560	400	3750

Table 5.7 Test results for #7 Aggregate + Natural Sand + C Ash mixture

Fresh properties									
Mix No	Type	Slump (in.)	Temp (F.)	Air Content (%.)	Unit.Wt lbs/ft^3	T-50 (sec.)	VSI	J-Ring (in.)	L-Box ratio
34	SCC	23.5	71	5.7%	137	1.12	1	22	0.65
35	SCC	28.75	77	6.4%	137	0.66	2	28.5	0.86
36	Conv.	4.75	73	5.6%	138	-	-	-	-
Fresh properties							**7-Day hardened properties**		
Mix No	**Type**	**Column segregation**	**AEA (oz/yd^3)**	**HRWR (oz/cwt)**	**Init.set (hr:min)**	**Fin.set (hr:min)**	**Fc (psi)**	**Splitting (psi)**	**E (Ksi)**
34	SCC	7.50%	1.2	5.8	6:20	8:15	4430	330	4100
35	SCC	8.60%	1.0	9.0	6:25	8:30	5200	435	4850
36	Conv.	-	2.7	0.0	5:30	7:10	5090	325	5100

Table 5.8 Test results for #7 Aggregate + Natural Sand + F Ash mixture

Fresh properties									
Mix No	Type	Slump (in.)	Temp (F.)	Air Content (%.)	Unit.Wt lbs/ft^3	T-50 (sec.)	VSI	J-Ring (in.)	L-Box ratio
46	SCC	24.5	76	6.0%	138	1.09	1	21.25	0.36
47	SCC	29	74	6.0%	137	0.47	2	28	0.75
48	Conv.	3.2	78	5.5%	138	-	-	-	-
Fresh properties							**7-Day hardened properties**		
Mix No	**Type**	**Column segregation**	**AEA (oz/yd^3)**	**HRWR (oz/cwt)**	**Init.set (hr:min)**	**Fin.set (hr:min)**	**Fc (psi)**	**Splitting (psi)**	**E (Ksi)**
46	SCC	6.9%	0.0	7.4	6:06	8:00	5260	310	5050
47	SCC	18.4%	0.0	10.7	7:51	9:48	2230	170	3900
48	Conv.	-	6.0	0.0	4:30	5:51	4090	360	3750

5.3 Discussion of Fresh Properties of Concrete Mixtures

5.3.1 Filling Ability and Visual Stability of SCC Mixtures

As mentioned earlier in Chapter 4, the slump flow test was conducted to measure the filing ability (deformability) of the studied mixtures. Different HRWR dosages were used to produce SCC mixtures with VSI of 1 and 2. The VSI values were determined through a visual rating of the slump flow patty. The T50 value is also another fresh property that was measured to quantify the flowing ability of SCC, and to provide a relative index of the viscosity. The results of slump flow, VSI, and T50 tests were obtained for different aggregate sizes as shown in Section 5.2 and summarized in Figures 5.1, 5.2, and 5.3. Each aggregate size is discussed below in more details.

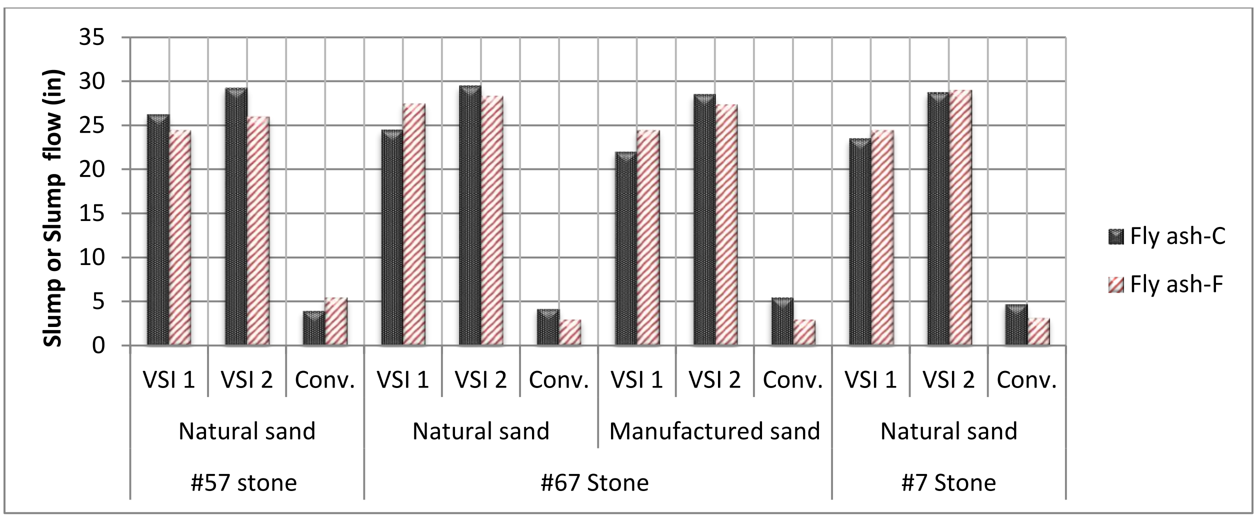


Figure 5.1 Slump and slump flow of the studied stones

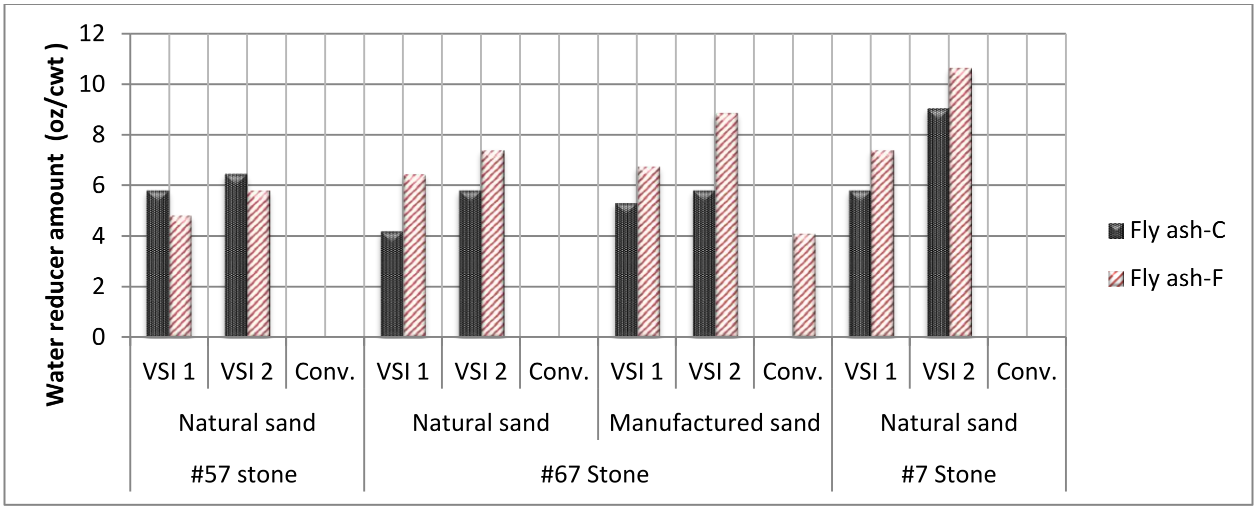


Figure 5.2 Water reducer admixture requirements for the studied stones

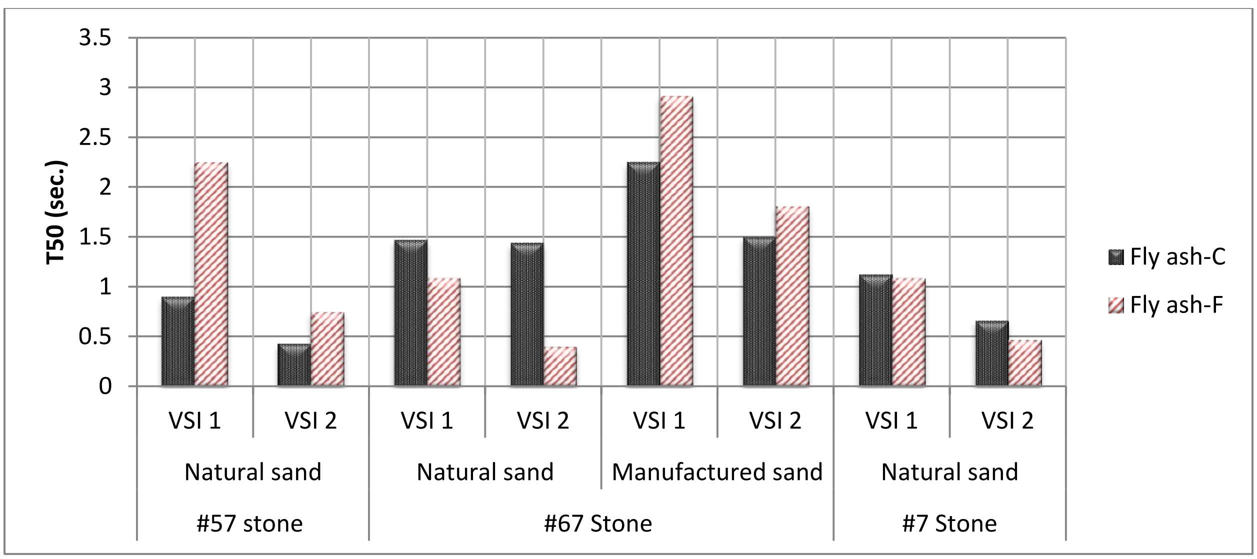


Figure 5.3 T50 values of the studied stones

5.3.1.1 Mixtures Containing Coarse Aggregate #57 with Natural Sand

Coarse aggregate #57 was the largest aggregate size used in this study which has maximum aggregate size of 1.0 in. A total of six mixtures, four SCC and two conventional, were produced using natural sand. Two classes of fly ash were used to replace 20% of the cement content; three mixtures (Mix No 25, 26, and 27) contained fly ash Class C and the other three contained fly ash Class F (Mix No 37, 38, and 39), as mentioned earlier in Chapter 4. The slump flow, VSI, and T50 results are represented in Tables 5.1 and 5.2, for #57 stone, and then summarized in the Figures 5.4 to 5.6.

Figure 5.4 shows the slump flow results for #57 stone, and it is obvious and anticipated that the mixtures with the VSI of 2 show higher slump flow compared with the VSI of 1, which is due to the high flowabilty of VSI of 2 mixtures and the higher HRWR dosages. As can be seen from Figure 5.4, all SCC mixes have slump flow within the range of 20 - 30 in, which is in agreement with the recommended slump flow range by most of the State DOTs specifications reported in Chapter 3. It may also be noticed from Figure 5.4 that the conventional concrete mixture produced using fly ash Class F shows higher slump than that made with Class C fly ash, without adding any water reducer admixtures.

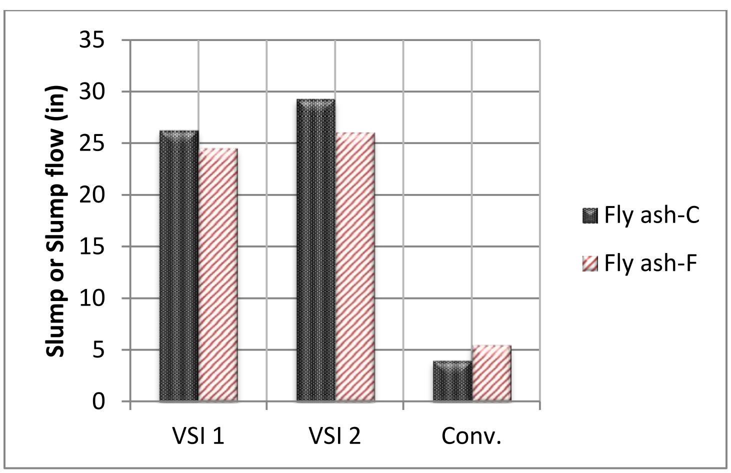


Figure 5.4 Slump and slump flow of #57 stone mixtures

Figure 5.5 summarizes the water reducer admixture requirements for #57 stone; it indicates that the fly ash Class C needs more WRA, to attain the VSI of 1 and 2, than that needed for Class F fly ash mixtures. Therefore it can be concluded the fact that fly ash Class F improves the flowability of #57 stone SCC mixtures with lesser amount of WRA than Class C fly ash mixtures. This fact is in agreement with ACI committee report 237 and FANG et al. (1999); they mentioned a replacement between 20 and 40% Class F fly ash in a SCC mixture could led to good workability. So the only reason behind having higher slump flow in the mixtures containing fly ash Class C, as shown in Figure 5.4, because of adding more HRWR to these mixtures to attain the desirable VSI values. For the same reason and as shown in Figure 5.6, the fly ash Class C mixtures show shorter T50 time than that of the fly ash Class- F mixtures. In accordance with the ACI Committee 237 report, a SCC mixture can be characterized as a lower viscosity mixture when the T50 time is 2 seconds or less, and as a higher viscosity mixture with T50 time greater than 5 seconds. Thus the #57 stone mixtures can be considered as lower viscosity mixtures.

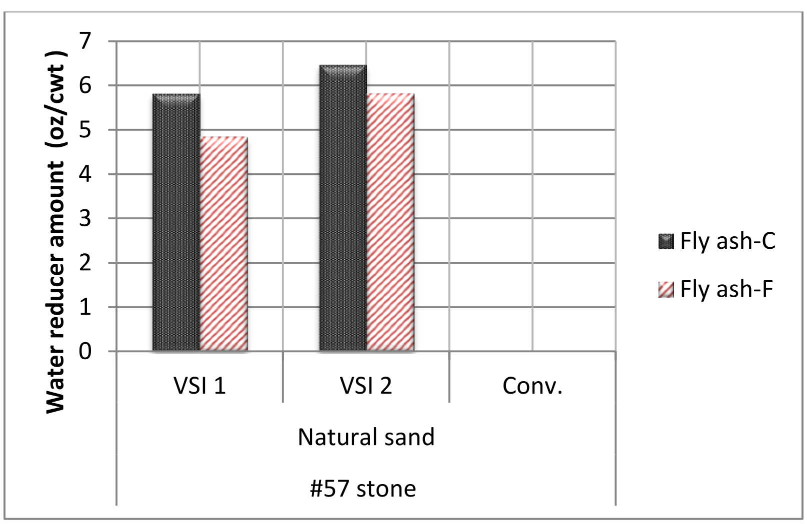


Figure 5.5 Water reducer admixture requirements for #57 stone mixtures.

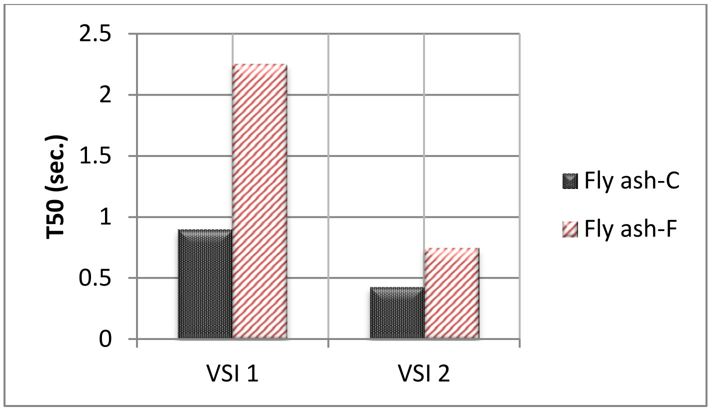


Figure 5.6 T50 values of #57 stone mixtures

5.3.1.2 Mixtures Containing Coarse Aggregate #67 with Natural and Manufactured Sand

Coarse aggregate #67 was recommended by many of the State DOTs specifications as described in Chapter 3. Coarse aggregate #67 has a maximum aggregate size of 3/4 in. A total of 12 mixtures, eight SCC and four conventional concrete, were produced using 67 stone. Six out of the 12 mixtures, were devolved using natural sand, three of them (Mix No 28,29, and 30) were produced with 20% cement replacement using fly ash Class C, and the other three (Mix No 40, 41, and 42) were produced using 20% cement replacement using Class F fly ash, as shown in Tables 5.3 and 5.4. The same six mixtures repeated using manufactured sand instead of the natural sand (Mix No 31, 32, 33, 43, 44, and 45) as shown in Tables 5.5 and 5.6.

The slump flow values and water reducer rdmixture requirements that are shown in Tables 5.3 to 5.6 were summarized in Figures 5.7 and 5.8. As can be seen from Figure 5.7, all SCC mixes have slump flow within the range of 20 - 30 in, and the mixtures with the VSI of 2 show higher slump flow than that of the VSI of 1, as same as #57 coarse aggregate.

It may also be noticed from Figure 5.7, the mixtures made with the natural sand shows slightly higher slump flow than that made with the manufactured sand, despite the higher amount of HRWR that was added to the manufactured sand as shown in Figure 5.8. This behavior could be attributed to the particle gradation and shape difference between the natural and manufactured sand. It should be noted that the Class C fly ash mixtures exhibit greater slump flow in both conventional and SCC with a VSI of 2 than Class F fly ash mixes. This performance was demonstrated despite Class F fly ash mixtures having greater water reducer dosages, as shown in Figure 5.8. The above performance exists in the #67 stone mixtures, but the opposite is true in the #57 stone mixtures, as discussed in Section 5.3.1.1.

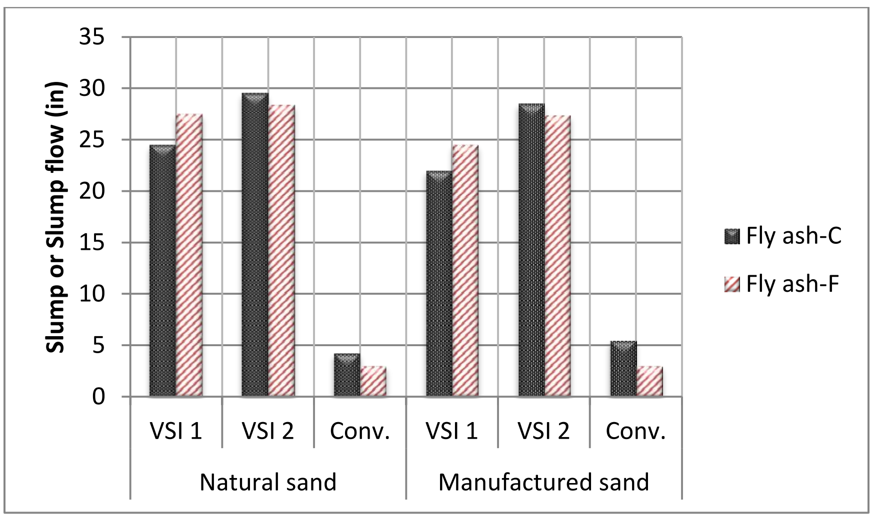


Figure 5.7 Slump and slump flow of #67 stone mixtures

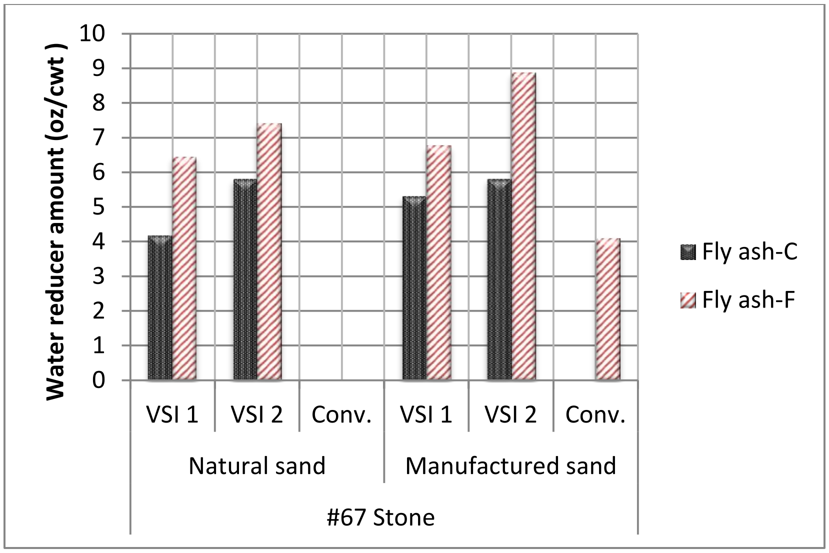


Figure 5.8 Water reducer admixture requirements for #67 stone mixtures

Figure 5.9 shows the T50 values for the #67 stone mixtures. Obviously, the mixtures containing natural sand show lower viscosity (T50 less than 2 sec.) than that containing manufactured sand. It is also notable; the natural sand mixed with the fly ash Class F is showing less viscosity, contrary to the manufactured sand; which is showing less relative viscosity with fly ash C. This behavior could be attributed to the particle gradation and shape difference between the natural and manufactured sand; the natural sands tend to be rounded shape whereas manufactured sands tend to be angular (Kandhal, Motter, & Khatri, 1991).

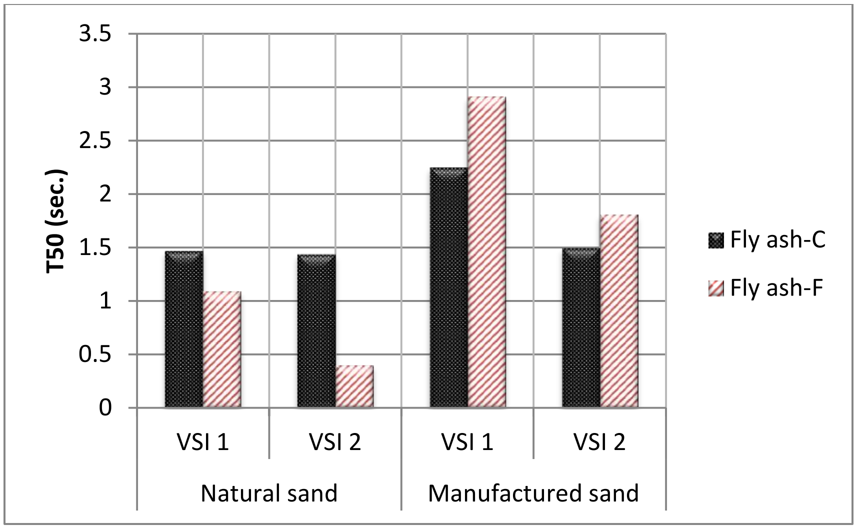


Figure 5.9 The T50 values of #67 stone mixtures

5.3.1.3 Mixtures Containing Coarse Aggregate #7 with Natural Sand

Coarse aggregate #7 was the smallest aggregate size used in this study, which has maximum aggregate size of 0.5 in. Similar to #57 stone and #67 stone, a total of six mixtures (Mix No 34, 35, 36, 46, 47, and 48) four SCC and two conventional, were produced using natural sand and fly ash Class F and C. The slump flow values, water reducer admixture requirements, and the T50 values that are shown in Tables 5.7 and 5.8 are summarized in Figures 5.10 , 5.11, and 5.12 respectively. It is clear in Figure 5.10 that all SCC mixes have slump flow within the range of 20 - 30 in. Also it is clear in Figure 5.11, using Fly ash Class C shows higher slump flow, in the conventional and SCC with VSI of 2, than the mixtures made with Class F fly ash. Despite the fact that a higher amount of HRWR was added to the Class F fly ash mixtures to attain the desirable VSI values. Therefore we can conclude that the fly ash Class C improves the flowability of #67 & #7 stone mixtures with less amount of WRA than Class F fly ash mixtures, which is adverse to the case of #57 stone, as discussed in Section 5.3.1.1. This phenomenon could be attributed to the large aggregate size of #57 stone, 1 in as maximum aggregate size, besides the chemical composition difference between fly ash Class F and C which could be the main reasons behind having different fly ash effects in the flowability of #57 stone and the other #7 and #67 stones.

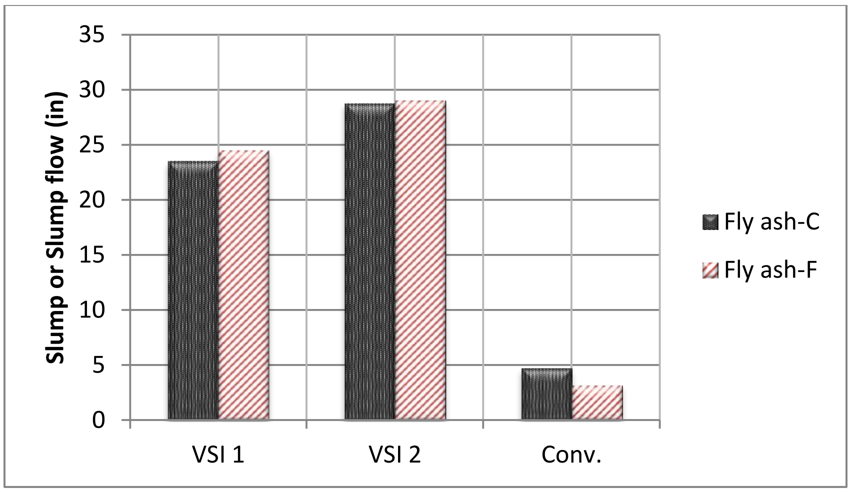


Figure 5.10 Slump and slump flow of #7 stone mixtures

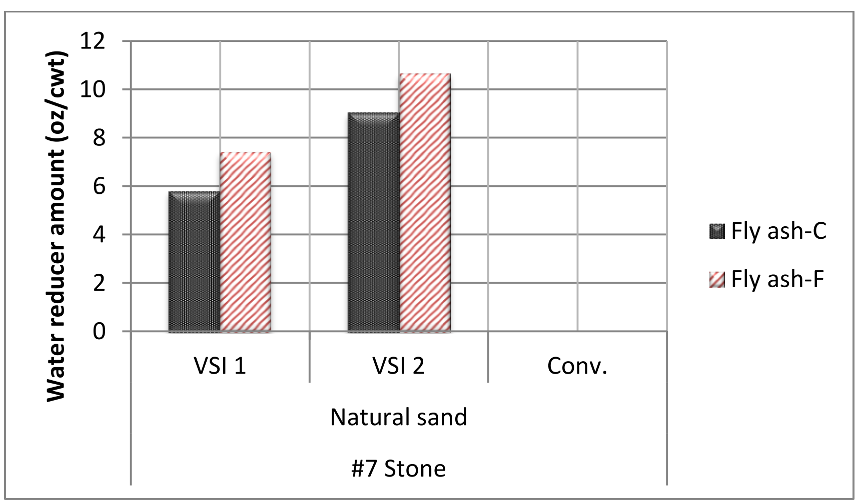


Figure 5.11 Water reducer admixture requirements for #7 stone mixtures

In Figure 5.12, as same as #67 stone with the natural sand, the fly ash Class F mixtures show shorter T50 time than that of the fly ash Class C mixtures, which is due to the high dosages of WRA that was added to Class F fly ash mixtures to attain the desirable VSI values.

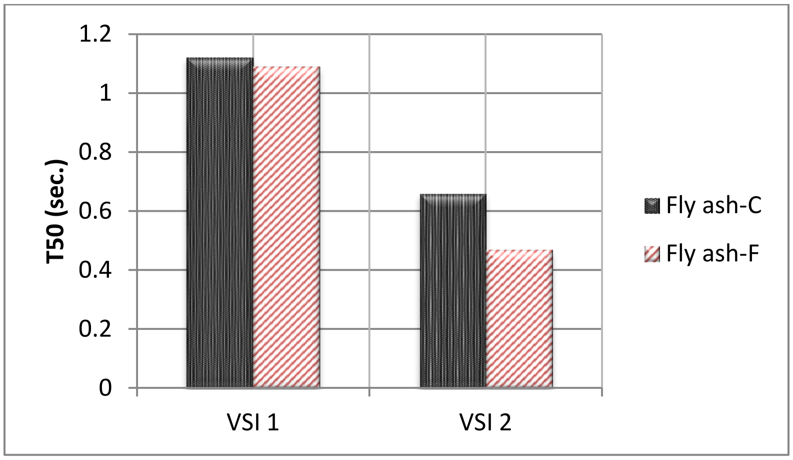


Figure 5.12 The T50 values of #7 stone mixtures

5.3.2 Passing Ability of SCC Mixtures

As mentioned before in Chapter 4, the J-ring and L-box tests were conducted to measure the passing ability of the studied mixtures. The mixtures passing ability and the blocking tendency could be identified according to the ASTM C1621 standard classification shown in Table 2.1 in Chapter 2. The ACI committee report 237 recommends the L-box ratio to be near to the 1.0 as an indication of good passing ability. The results of J-ring and L-box tests were obtained for different aggregate sizes as described in Section 5.2 and summarized in Figures 5.13 and 5.14. The results of each aggregate size are discussed in the following section.

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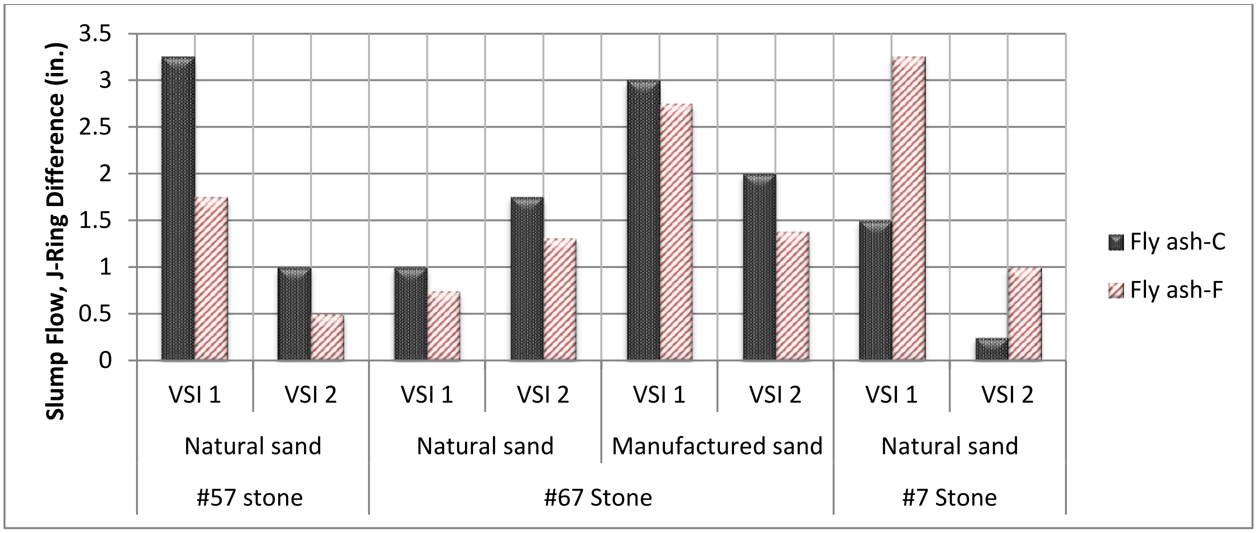

Figure 5.13 Slump flow and J-ring difference for the studied stones

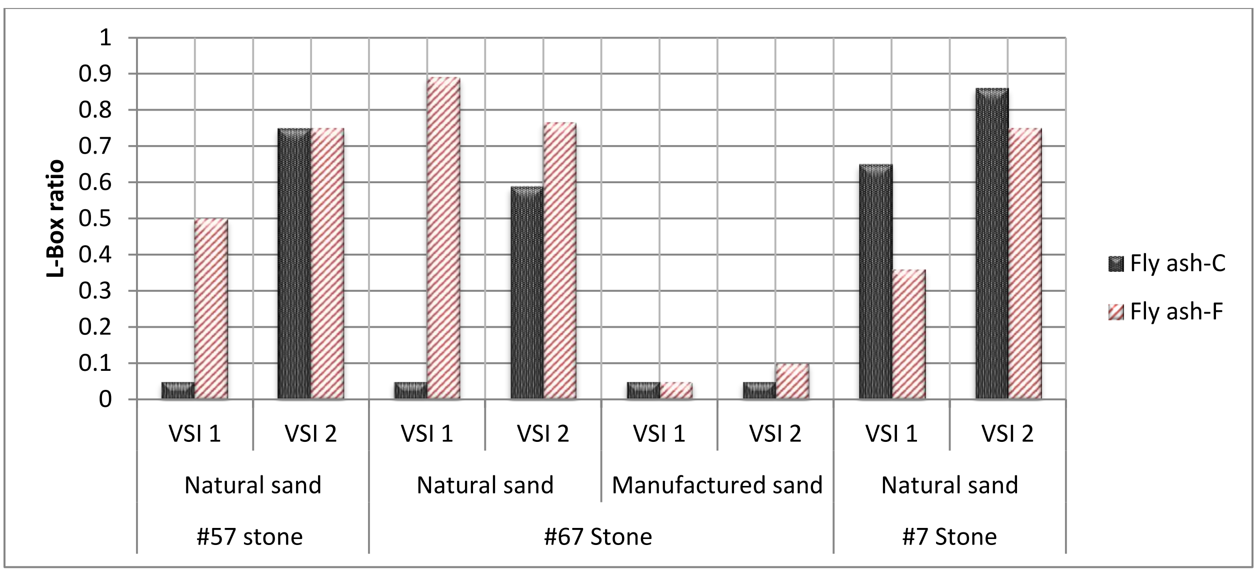

Figure 5.14 The L-Box Ratio for the studied stones

5.3.2.1 Mixtures Containing Coarse Aggregate #57 with Natural Sand

Figure 5.15 below shows the difference between the slump flow and J-ring values, which are shown in Tables 5.1 and 5.2 for #57 stone mixtures. As can be seen from Figure 5.15, the mixtures with VSI of 2 showed better passing ability than that of VSI of 1 mixture, which is anticipated and attributed to the high flowabilty of VSI 2 mixtures. It may also be observed, the mixtures containing fly ash Class F show better passing ability than that of fly ash Class C mixtures, about half the difference. In addition, Most of the State DOTs specifications specify the difference between the conventional slump flow and the J-ring slump flow to be less than 2 inches (minimal to noticeable blocking), which is in agreement with the results of the mixtures containing fly ash F, as shown in Figure 5.15.

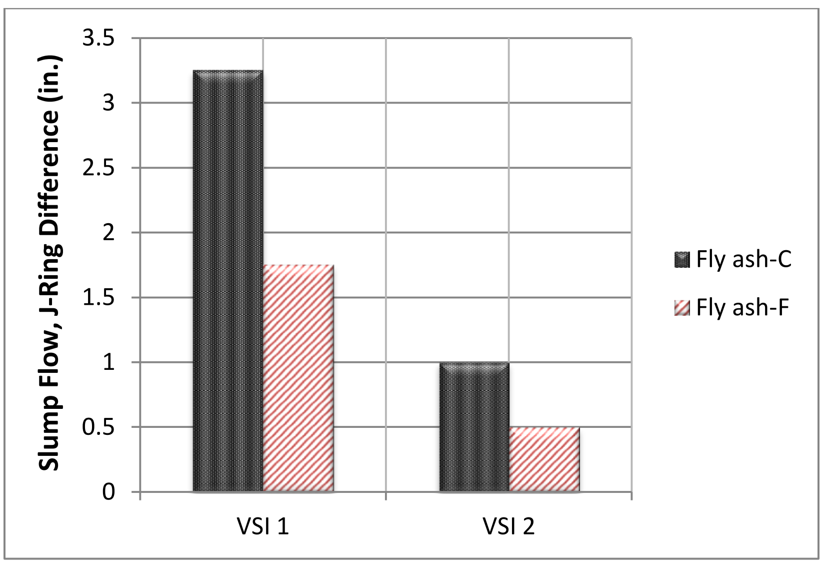

Figure 5.15 Slump flow and J-ring difference for #57 stone mixtures

As can be seen from Figure 5.16, which is showing the L-box ratio for #57 stone, using fly ash Class F produced L-box ratio of 0.5, in the VSI of 1 mixture, compared to the zero L-box ratio (Blocking) resulted from using fly ash Class C. The large aggregate size of #57 stone and the weak flowability of VSI of 1 mixture could be the main reason of having blocking in L-box test. On the other hand, the VSI of 2 showed higher passing ability compared to that of VSI of 1, which is in agreement with the results of J-ring test shown in Figure 5.15.

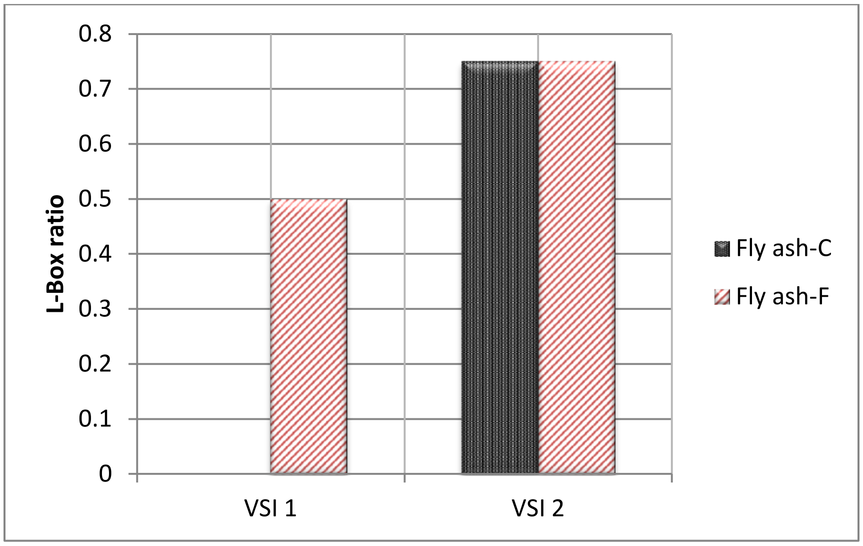

Figure 5.16 The L-Box Ratio for #57 stone mixtures

5.3.2.2 Mixtures Containing Coarse Aggregate #67 with Natural and Manufactured Sand

As shown in Figure 5.17, the manufactured sand shows very low passing ability (noticeable to extreme blocking) than that of the natural sand, especially in the VSI of 1 mixtures. Similar to #57 stone, the fly ash Class F improves the passing ability of the #67 stone mixtures, which is clear in Figure 5.17 that all the fly ash Class F mixtures show less slump flow and J-ring difference (high passing ability, No visible blocking) than that of fly ash Class C. It can be observed from Figure 5.12, all #67 stone mixtures are in agreement with the State DOTs specifications (less than 2 in. difference), except the manufactured sand with the VSI of 1 shows more than 2 in. difference between the slump flow and J-ring . Another sign of the poor passing ability of the manufactured sand can be seen clear in the L-box results as shown in figure 5.18, which is showing blocking (zero L-box ratio) in the VSI of 1 mixture and only 0.1 L-box ratio in the VSI of 2.

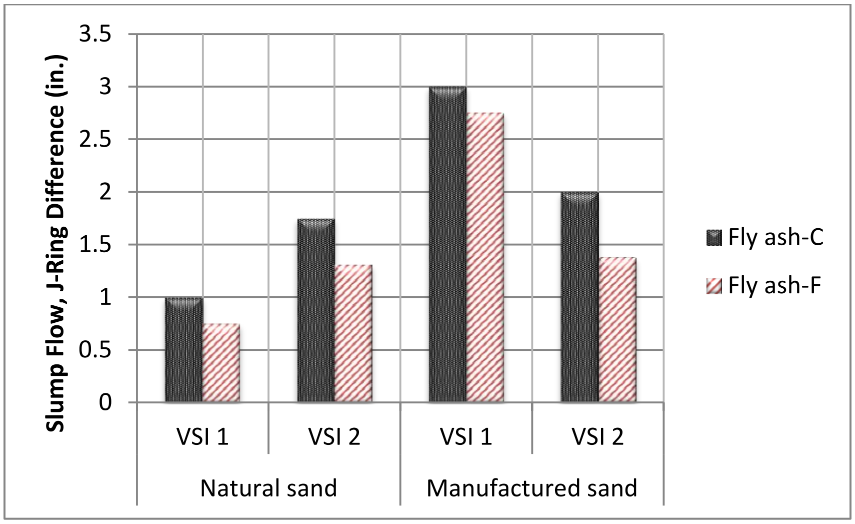

Figure 5.17 Slump flow and J-ring difference for #67 stone mixtures

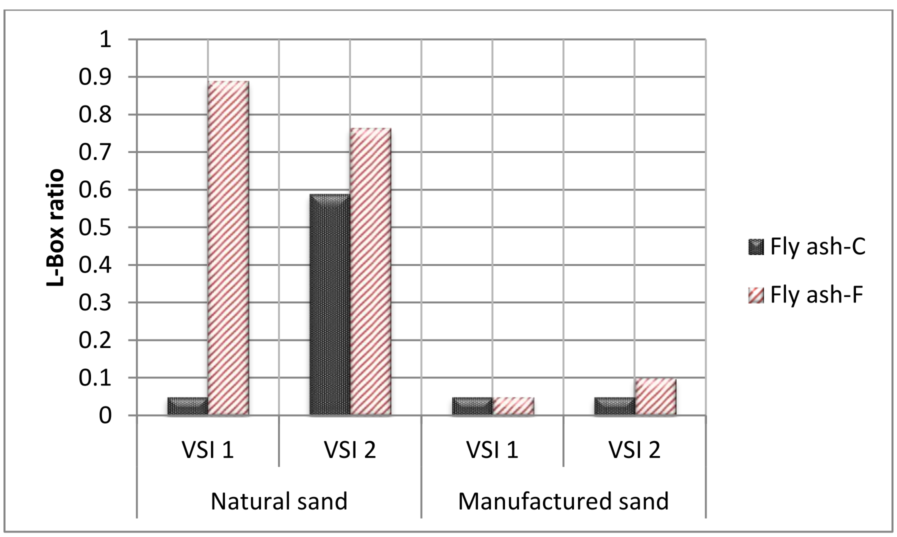

Figure 5.18 The L-Box Ratio for #67 stone mixtures

5.3.2.3 Mixtures Containing Coarse Aggregate #7 with Natural Sand

As shown in Figure 5.19, the coarse aggregate #7 has good passing ability (No visible blocking) in the VSI of 2 mixtures, and a noticeable to extreme blocking in the VSI of 1 mixtures. Similar to #57 and #67 stones mixture results, the fly ash Class F shows good passing ability compared to that of Class C fly ash. That could be attributed to the difference in calcium oxide content between the two classes of fly ash; which causes different effects on the fresh properties of SCC, as mentioned by SKeske 2011.

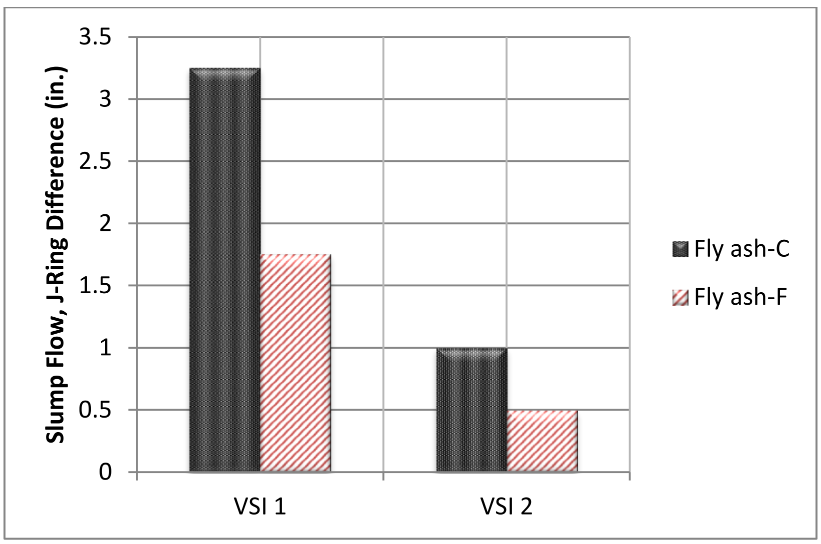

Figure 5.19 Slump flow and J-ring difference for #7 stone mixtures

Figure 5.20 summarizes the L-box results for #7 stone that shown in Tables 5.7 and 5.8. There is a notable different effect of fly ash Class F in # 7 stone than that in the #57 and #67 stones. As have been noticed in the L- box results for #57 and #67 stones, shown in Figure 5.16 and 5.18 respectively, the fly ash Class F shows more passing ability (high L-Box ratio) than that of fly ash Class C. This is not the case in the Figure 5.20; the fly ash Class C shows more passing ability than that of fly ash Class F. This phenomenon could be attributed to the small size of aggregate #7 stone, which could be the main reason behind having different fly ash effects in the L-box test for #7 stone and the other #57 and #67 stones. In general L-box test showed some difficulties; high force accompanied by some vibrations was applied while lifting the gate which affected the test accuracy and precision.

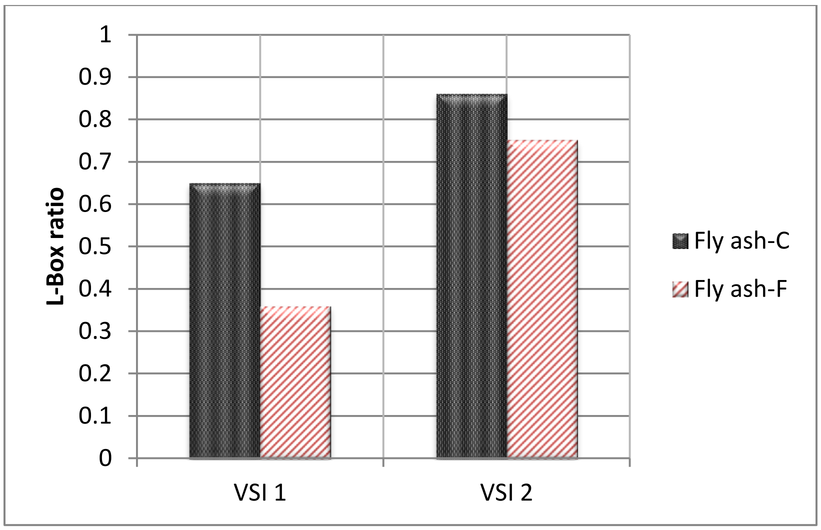

Figure 5.20 The L-Box Ratio for #7 stone mixtures

5.3.3 Stability of SCC Mixtures

The Column Segregation test was used to assess the segregation resistance of SCC mixtures. The SCC is generally considered to be accepted if the percent-segregation is less than 10% (ACI, 2007). However, some of the State DOTs specifications specify 15% as a maximum column segregation limit. The results of the Column Segregation test were obtained for different aggregate sizes as described in Section 5.2 and summarized in Figure 5.21. Most the VSI 1 mixtures meet the 10% limit and all meet the 15% requirements as shown in Figure 5.21. Each aggregate size is discussed proceeding sections.

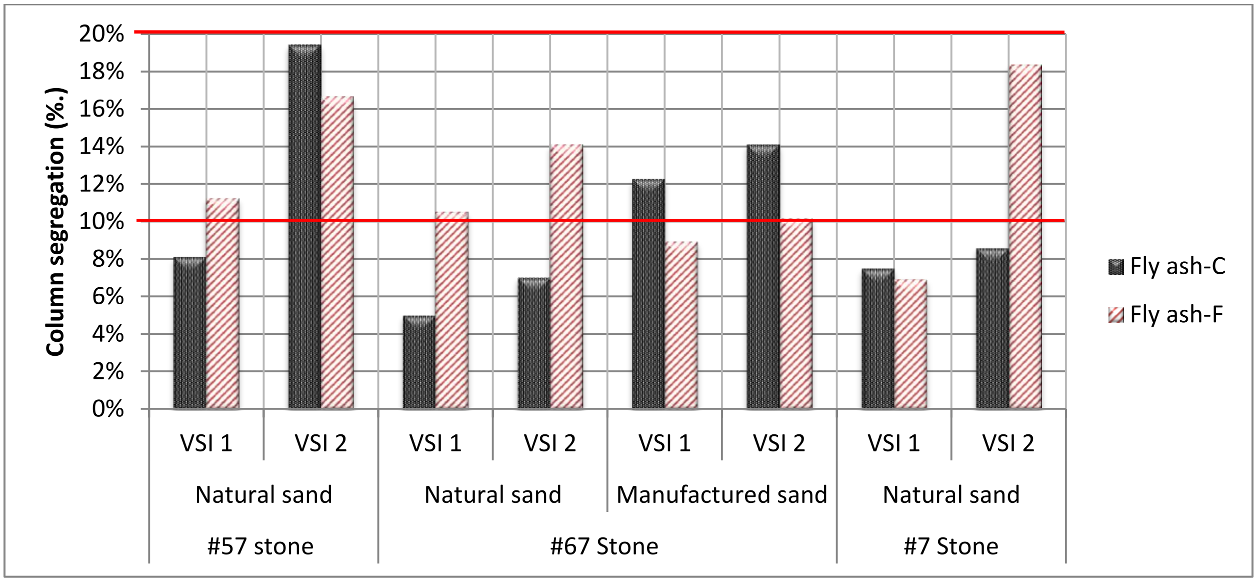

Figure 5.21 The column segregation for the SCC mixtures

5.3.3.1 Mixtures Containing Coarse Aggregate #57 with Natural Sand

As mentioned earlier in this Chapter, the #57 coarse aggregate is the largest aggregate size used in this study. Thus, it was anticipated to see high segregation potential for #57 stone mixtures due to the gap gradation of #57 stone shown in Figure 4.1. So it can be seen clearly in Figure 5.22 the VSI of 2 mixtures possess high segregation values (between15% to 20%) which are incompatible with the ACI requirements (greater than 10%). Conversely, the VSI of 1 shows reasonable segregation, especially in the mixtures containing fly ash Class C and it is in agreement with the ACI requirements.

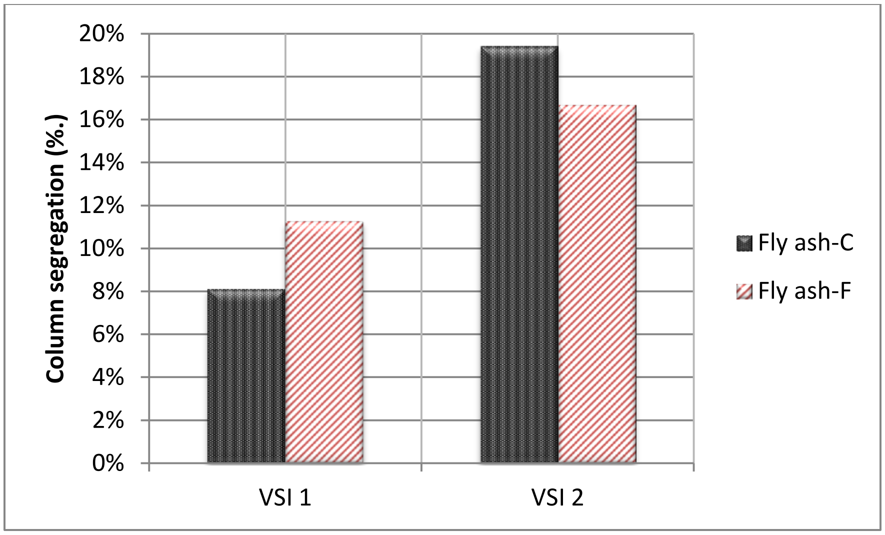

Figure 5.22 The column segregation for #57 stone mixtures

5.3.3.2 Mixtures Containing Coarse Aggregate #67 with Natural and Manufactured Sand

It may be noticed from Figure 5.23, the natural sand shows a little less segregation potential than that of the manufactured sand. Also, it can be seen clearly, the VSI of 2 for the mixtures containing the manufactured sand show high segregation values (greater than 10%) which are incompatible with the ACI requirements. It is also notable, and in agreement with #57 stone, the fly ash Class C shows lower segregation potential, in the natural sand mixtures with VSI of 1, than that of Class F fly ash mixture. While the manufacture sand adversely shows lower relative segregation potential with fly ash Class F rather than Class C. This contradiction in the fly ash effects could be attributed to the difference in natural and manufactured sand gradation and particles shape.

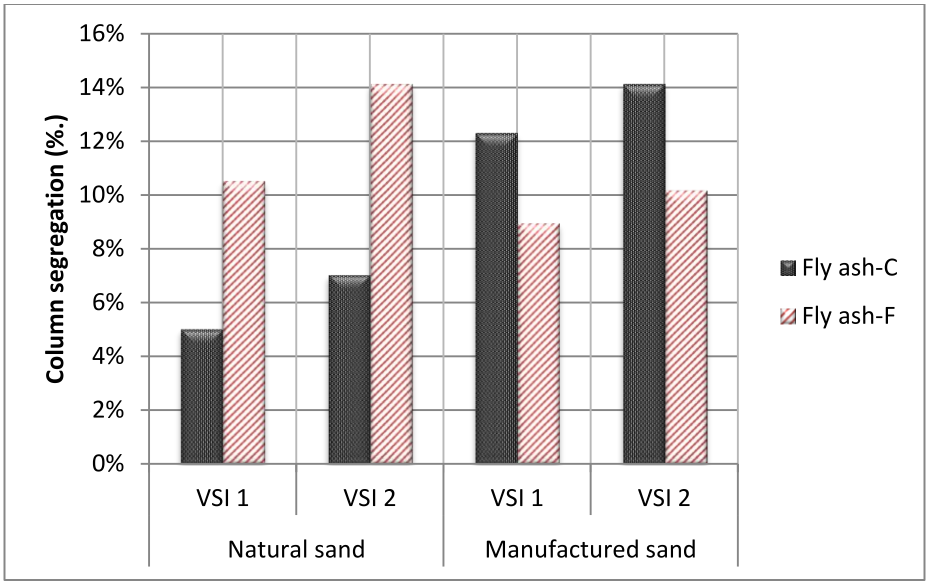

Figure 5.23 The column segregation for #67 stone mixtures

5.3.3.3 Mixtures Containing Coarse Aggregate #7 with Natural Sand

The coarse aggregate #7 was the smallest size used in this study. Therefore it was anticipated to show less segregation potential than that of the other aggregate sizes. This trend could also be attributed to the well-graded #7 stone mixtures as show in Figure 4.1. Studies show that the well-graded mixtures tend not to have as many problems as gap-graded mixes in terms of workability and segregation during vibration (Richardson, 2005). As observed from Figure 5.24, all the mixtures show acceptable segregation potential except the one with the 18.35 % segregation. This high segregation value could be attributed to the high amount of HRWR that was added in this mixture as shown in Figure 5.11.

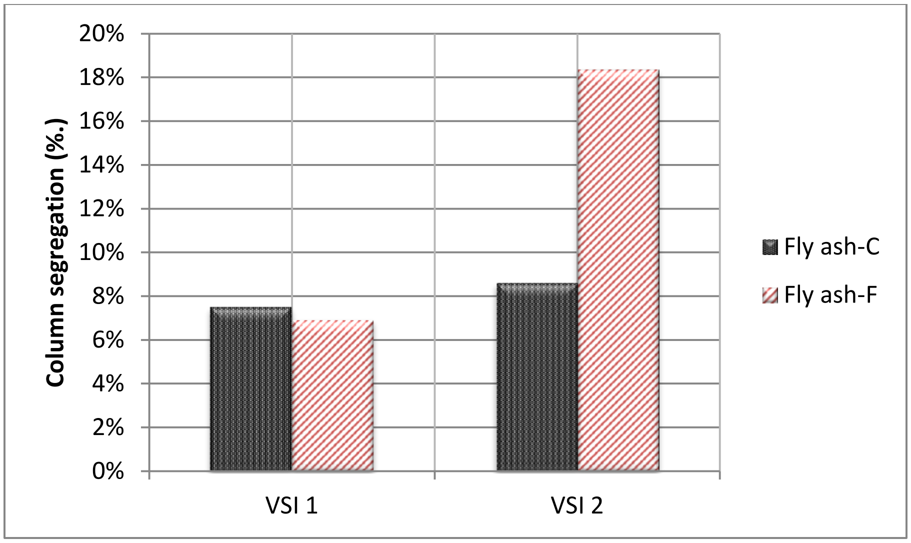

Figure 5.24 The Colum Segregation for #7 stone mixtures

5.3.4 Initial and Final Time of Setting for SCC and Conventional Concrete Mixtures

The Time of setting of concrete mixtures by penetration resistance was conducted for the both SCC and conventional concrete mixtures. The test was conducted on a mortar sample that was obtained by sieving a representative sample of fresh concrete through a 4.75-mm sieve. Thus it was not anticipated to notice much variation between the different aggregate sizes. The results of the different aggregate sizes are discussed below in details.

5.3.4.1 Mixtures Containing Coarse Aggregate #57 with Natural Sand

Figure 5.25 shows the initial and final time of setting for #57 stone, which ranged between 5 to 8.5 hours, and it was anticipated to notice such variation between the setting time between VSI of 1 and 2 and the conventional mixtures. This variation in the time of setting can be attributed to the different HRWR dosages among the mixtures; the VSI of 2 possessed the highest HRWR dosage and it showed higher time. In addition, it is noticeable that fly ash Class F is showing longer setting time than that of fly ash Class C, which due to the chemical composition deference between C and F fly ash; fly ash Class C contains higher amount of calcium oxide than fly ash Class F.

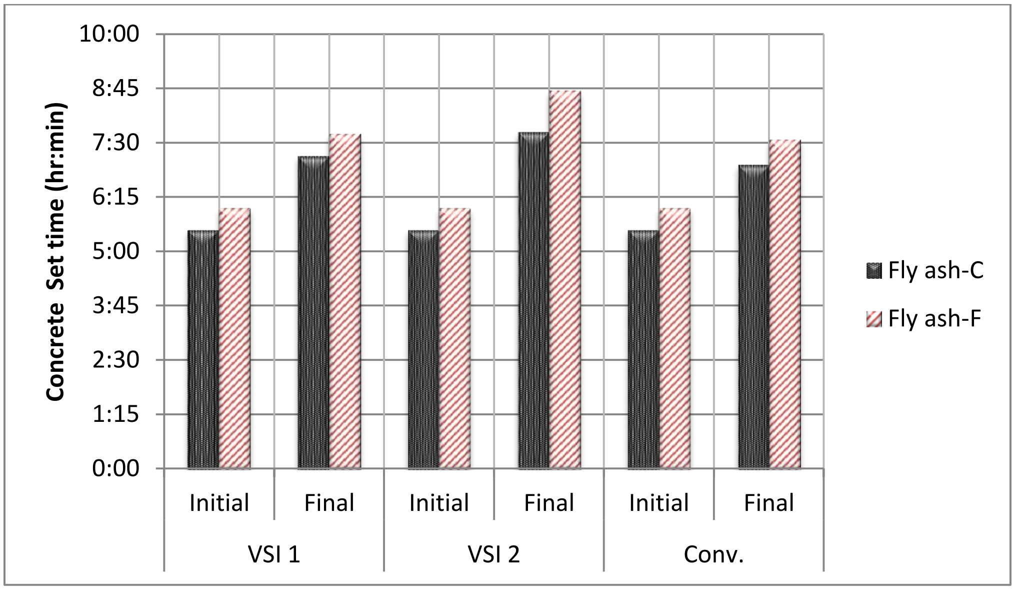

Figure 5.25 The initial and final time of setting for #57 stone mixtures

5.3.4.2 Mixtures Containing Coarse Aggregate #67 with Natural and Manufactured Sand

As shown in Figure 5.26, the natural sand shows quicker setting time than that of the natural sand. Which could be due to the different particles gradation of the manufactured sand; which was contained larger particles than that of the natural sand. Also it can be seen, similar to #57 stone, the fly ash Class C shortened the initial and final time of setting more than that of Class F fly ash.

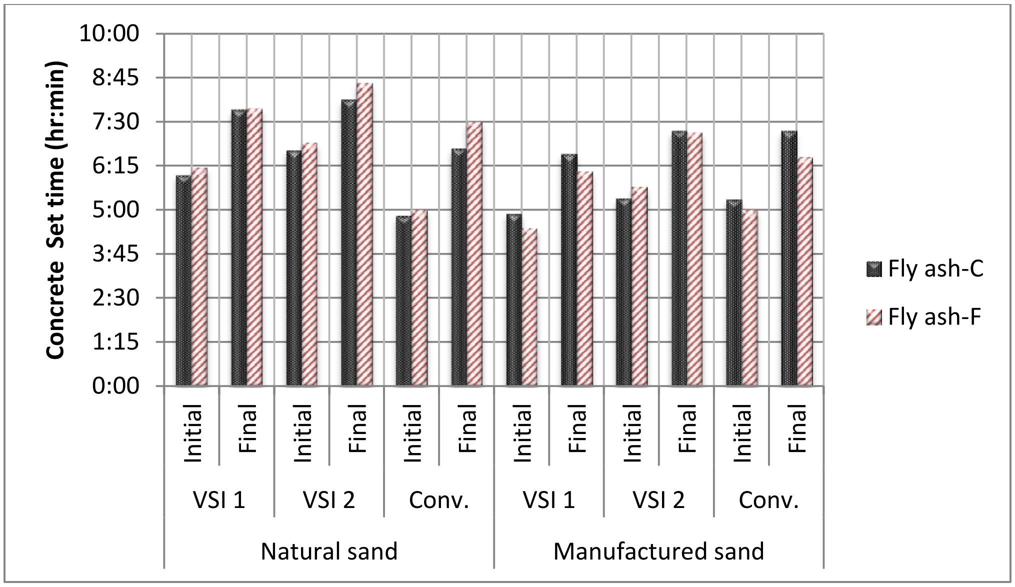

Figure 5.26 The initial and final time of setting for #67 stone mixtures

5.3.4.3 Mixtures Containing Coarse Aggregate #7 with Natural Sand

The same observations that were noticed in Figures 5.25 and 5.26 could be confirmed in Figure 5.27 for #7 stone.

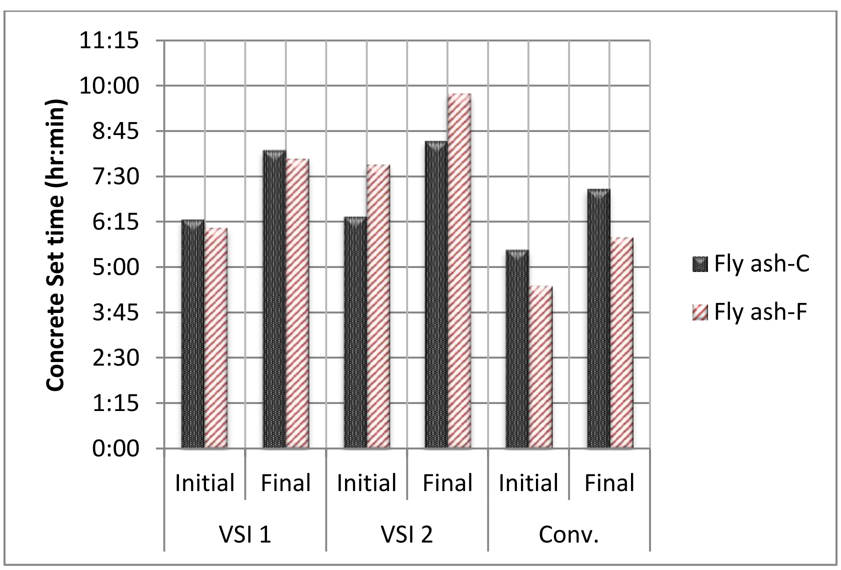

Figure 5.27 The initial and final time of setting for #7 stone mixtures

5.3.5 Air Entrained Admixture Requirements for Concrete Mixtures

As mentioned earlier in Chapter 4, the AEA was used to provide 5.5 % to 7.5 % air content within the concrete mixtures. The dosages of AEA for the different aggregate sizes are discussed below.

5.3.5.1 Mixtures Containing Coarse Aggregate #57 with Natural Sand

As can be seen in Figure 5.28, the SCC mixtures (VSI 1 and 2) require less AEA dosages than that for the conventional concrete mixture. This could be attributed to the HRWR effect which reduces the amount of air-entraining admixture necessary to achieve a given air content, as mentioned by Skeske 2011.

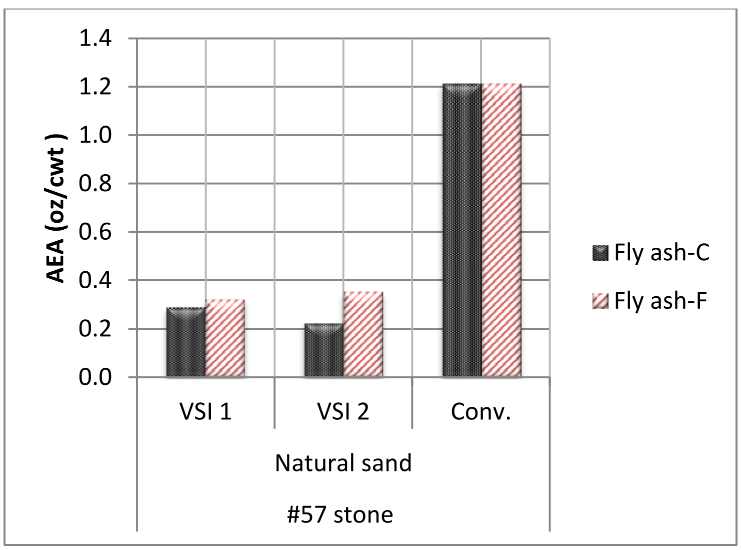

Figure 5.28 The AEA requirements for #57 stone mixtures

5.3.5.2 Mixtures Containing Coarse Aggregate #67 with Natural and Manufactured Sand

The same observations that have noticed in Figures 5.28 can be confirmed in Figure 5.29 for #67 stone mixtures. It can also be observed; the natural sand requires more AEA dosages to attain the desirable air contents than that for the manufacture sand, which can be attributed to the effect of different gradation between the natural and manufactured sand.

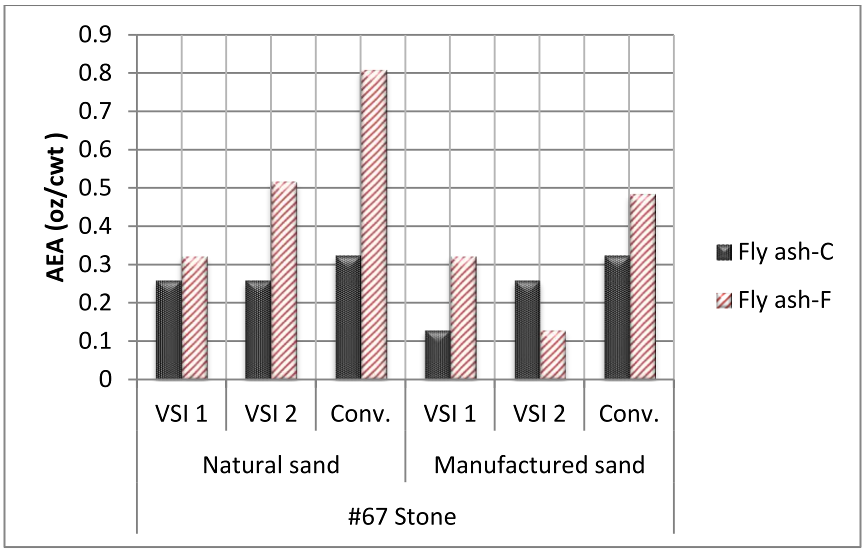

Figure 5.29 The AEA requirements for #67 stone mixtures

5.3.5.3 Mixtures Containing Coarse aggregate #7 with Natural Sand

It can be seen clearly in Figure 5.30, the #7 coarse aggregate needed less AEA dosages than that for #57 and #67 aggregate, as shown in Figures 5.28 and 5.29 respectively. The small aggregate size of #7 could be the main reason behind the AEA reduction.

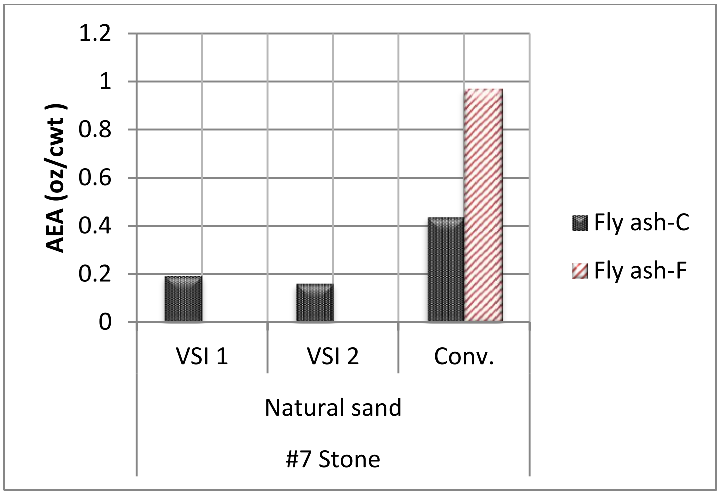

Figure 5.30 The AEA requirements for #7 stone mixtures

5.4 Discussion of Hardened Properties of Concrete Mixtures

As the fresh properties of concrete mixtures is the primary focus of this study, only the seven day compressive strength for the studied mixtures was discussed below.

5.4.1 The 7-day Compressive Strength for The Studied Mixtures

Figure 5.31 shows the 7-day compressive strength results for different aggregate sizes as described in Section 5.2. Most of mixtures showed 4,000 to 5,000 psi in the 7-day compressive strength test. It can be observed, the compressive strength of VSI of 2 is little less than that of VSI of 1. This could be attributed to the higher segregation tendency of VSI of 2 mixtures. For the same reason the VSI of 2 mixture with #7 stone showed low compressive strength which is due to the high segregation and high amount of HRWR that was added in this mixture as shown in Figure 5.11 and 5.24. Also, it is noticeable in Figure 5.31, the fly ash Class F shows less compressive strength than that of the fly ash Class C, which is in agreement with Mehta and Monteiro 2006; early strength gains at three and seven days are reduced more when using fly ash

Class F than when using Class C, as mention by Skeske 2011. This is because Class C fly ash is partly cementitious in nature due to its higher Calcium Oxide content, whereas Class F fly ash is almost completely pozzolanic in nature and is much slower to hydrate.

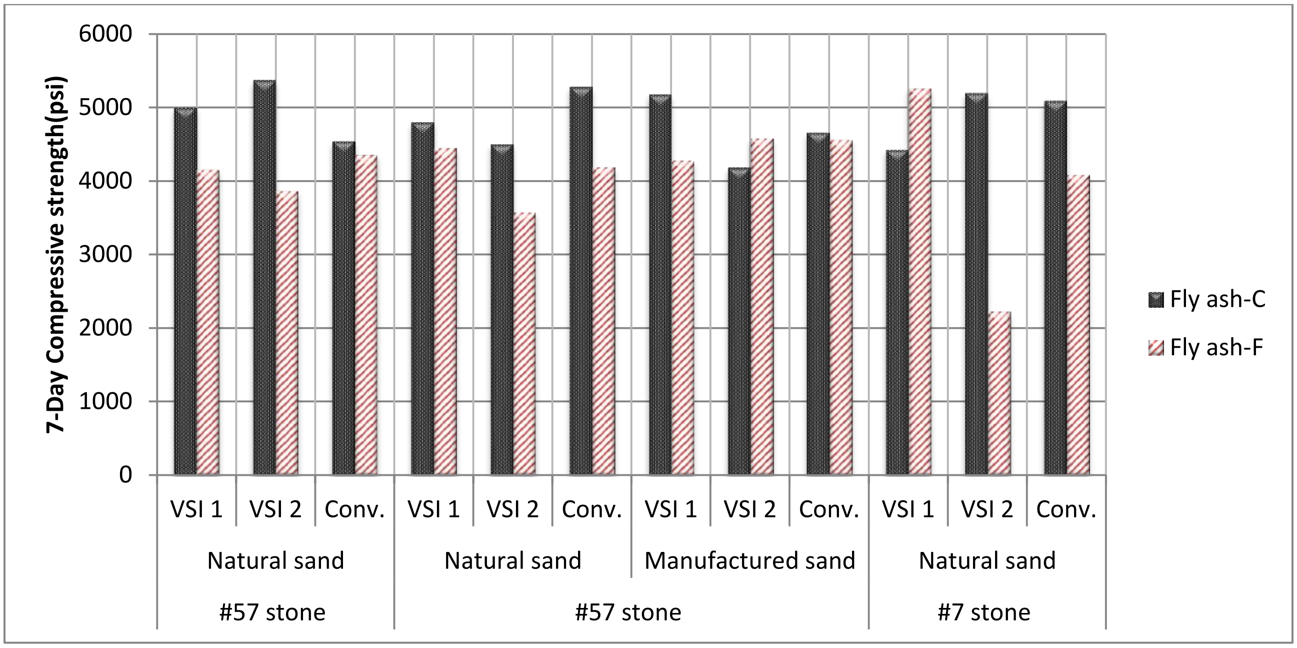

Figure 5.31 The 7-Day compressive strength of the studied mixtures

CHAPTER 6

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

6.1 Summary

This study is part of the a study funded by the Tennessee Department of Transportation (TDOT) carried out by University of Tennessee at Chattanooga (UTC) to develop four new SCC mixtures two precast and two general use, and insure they meet the minimum strength and durability requirement for TDOT Class P (precast) and Class A (general use) mixtures. This study only addressed the Class A (general use) mixtures which were selected for detailed studies of their fresh properties. The primary aims of this study were to investigate the fresh properties of Class A SCC using different aggregate sizes (ASTM C 33 #57, #67, and #7 stone), natural and manufactured sand, and using two classes of fly ash C and F. In addition, it aimed to investigate the effects of Visual stability index (VSI) on fresh segregation of SCC mixtures.

Before developing the trial mixtures of Class A concrete, the survey of state Departments of Transportation (DOTs) was conducted to gather specifications related to SCC use for general and precast elements in other states. The survey addressed the mixture parameters, fresh performance requirements, and the hardened performance requirements. The findings of the survey were summarized in Chapter 3 and then used to develop and select the mixture proportions and components, and choose the appropriate methods to evaluate the fresh characteristics of SCC mixtures.

Two Class A mixtures were designed with 20% cement replacement using fly ash class C for one mixture, and class F for the other. Each Class A mixtures duplicated 12 times with an array of visual stability index values of 1 and 2, different aggregate sizes (#57,#67, and # 7), and with natural and manufactured sand as discussed in Chapter 4.

Many methods were conducted to evaluate the fresh properties and characteristics of SCC mixtures which are described in Chapter 4 and summarized below:

- Slump flow test, Visual Stability Index, and T50 time were conducted to assess the filling ability of SCC mixtures,
- J-ring and L-box tests were conducted to assess the passing ability of SCC mixtures, and
- Column Segregation test was used to assess the fresh stability of SCC mixtures.

The fresh property test results from the 24 mixtures were collected based on the VSI values of 1 and 2 and then compared with each other and with the results of conventional concrete mixtures. Then, the observations, conclusions, and the recommendation made during the collection and analysis of these fresh property results are discussed below.

6.2 Observations and Conclusions

6.2.1 Observations and Conclusions from #57 Stone Concrete Mixtures

- The #57 stone mixed with natural sand exhibited acceptable filling ability. The fly ash Class F improves the flowability of #57 stone SCC mixtures with less amount of WRA than Class C fly ash mixtures.
- The #57 mixtures, containing natural sand and Class C fly ash, exhibited acceptable passing ability with the VSI of 2, and poor passing ability with the VSI of 1. While using fly ash Class F provides acceptable passing ability in the both VSI of 1 and 2.

- A high segregation tendency is expected in the #57 stone mixtures with VSI of 2. Using fly ash Class C in the #57 stone mixtures could reduce the segregation potential.
- The VSI of 2 mixtures possess longer setting time than that of VSI of 1 mixture. Using fly ash Class F can lengthen the setting time more than that of fly ash Class C.

6.2.2 Observations and Conclusions from #67 Stone Concrete Mixtures

- The natural sand provides higher slump flow and good filling and passing ability for #67 stones than that of the manufactured sand. The manufactured sand possesses a poor passing ability and high segregation potential (greater than 10% Column Segregation).
- Using fly ash Class C improves the flowability of #67 stone mixtures with less amount of WRA than that with using Class F fly ash. In addition, using Class C can reduce the segregation potential of #67 stone mixtures.
- The mixtures containing natural sand show lower viscosity (T50 less than 2 sec.) and longer setting time than that containing manufactured sand.
- The fly ash Class F improves the natural sand viscosity and passing ability, while the fly ash Class C improves the manufactured sand viscosity and reduces its segregation potential.
- Generally, The #67 stone mixtures show better fresh properties than that of #57 stone mixtures.

6.2.3 Observations and Conclusions from #7 Stone Concrete Mixtures

- In general, the #7 stone is more convenient for making the SCC mixtures and it exhibits acceptable characteristics (filling, passing, and stability) than the other #57 and #67 stones.

- The fly ash Class C improves the flowability of #67 & #7 stone mixtures with less amount of WRA than Class F fly ash mixtures.
- The coarse aggregate #7 that contains fly ash Class F has acceptable passing ability in the both VSI of 1 and 2 mixtures.

6.3 Recommendations

- The results of this study have indicated that SCC mixes made with the #57 stone, #67 stone, or manufactured sand, with the VSI value of 2, show high segregation potential. Therefore VSI value of 2 is not recommended with these aggregates.
- The #7 aggregate is highly recommended in order to produce SCC mixtures with high flowability, high passing ability, and with less segregation potential.
- It is not recommended to use the manufacture sand as pure fine aggregate in the SCC mixtures; it shows high segregation potential and poor passing ability.
- Using fly ash C and F is very important to improve the fresh characteristics of SCC mixtures.
- It is also recommended for future work to investigate the fresh properties of using a blended fine aggregate with natural and manufactured sand and study their effect on the fresh characteristics of SCC. In addition, the #7 stone mixtures with HRWR show low or no air entraining agent dosages to provide their design air contents, so it is recommended for future work to study the air voids produced by the HRWR alone to make sure they provide resistance to the damage by freeze/thaw cycles.

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VITA

Ammar Elhassan was born in Sudan, Nyala, on 31 December 1988, the son of Elfatih Abdelssamd and Thouraya Elmahadi. He is the fifth of six children, older three brothers and one sister and a younger one brother. He received his Bachelor degree of Civil Engineering from University of Khartoum, Sudan, in September 2010. After graduation, during 2010 – 2012, he worked for Asawer Oil and Gas Company, Sudapet, as a Civil and Structural Engineer and for the University of Khartoum as a Teaching Assistant which was the impetus for him to continue his higher education. Ammar moved to USA in August 2012 after accepting a graduate research assistantship at the University of Tennessee at Chattanooga in the Master of Civil Engineering Program. He graduated with a Master's of Science degree in Engineering in August 2014.